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Noise-induced hearing loss: research update from 2023 to 2025 in humans

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ABSTRACT

Noise-induced hearing loss (NIHL) remains one of the most prevalent yet preventable causes of sensorineural hearing loss worldwide, affecting individuals across the lifespan through occupational and leisure noise exposure. This narrative review provides an update on human research published between 2023 and 2025. A search of the Web of Science Core Collection identified 570 records, of which 130 original human studies met the inclusion criteria and were synthesized. The reviewed literature confirms the persistent global burden of NIHL and highlights its multisystem consequences, extending beyond auditory impairment to include tinnitus, balance disorders, hidden hearing loss, cognitive and emotional impairments, and reduced quality of life. Key research themes included the prevalence and characterization of NIHL in diverse populations, occupational and non-occupational risk factors such as duration and type of noise exposure, co-exposures, and individual susceptibility, and advances in diagnostic and management approaches. Notable progress was observed in electrophysiological and speech-in-noise measures, biomarkers, neuroimaging, and artificial intelligence–based predictive models, contributing to improved early detection and risk stratification. Preventive strategies, including hearing conservation programs, hearing protection devices, educational interventions, and emerging therapeutic approaches were widely investigated. However, despite scientific and technological advances, substantial gaps persist in the translation of knowledge into sustained preventive behaviours, workplace practices, and public health policies. Integrated approaches combining biological, technological, behavioural, and educational strategies remain essential to reduce the prevalence and impact of NIHL and to improve long-term outcomes for noise-exposed populations.

INTRODUCTION

The impacts of occupational noise exposure on health between 1990 and 2021 were analyzed, and despite a slowdown in its growth rate, a global increase in disability-adjusted life years (DALYs) related to occupational noise was observed, driven by population changes and population aging. Epidemiological changes (health and safety policies and control measures) had a minimal effect on DALYs, suggesting that the effectiveness of mitigating the burden of disease through occupational health management has been limited. Although

DALYs have decreased significantly with increasing sociodemographic index, low-income and rapidly industrializing countries have shown higher burdens of noise-related diseases. These data highlight significant regional disparities in occupational noise-related DALYs and the need to strengthen public policies that address these issues [1].

Noise-induced hearing loss (NIHL) is the second leading cause of sensorineural hearing loss (HL), after age-related HL [2], and can be associated with substantial physical, mental, social, and economic impacts on the individual and society [3]. However, NIHL is largely a preventable condition when appropriate measures are taken [2,3]. Globally, NIHL is estimated to affect approximately 5% of the population, being more common among men. However, this prevalence may be underestimated due to inequalities between different countries [3].

Our objective was to provide an update on research on NIHL in humans, including publications from 2023 to 2025, presented through a narrative-style review.

METHODS

This study was conducted as a narrative review to provide an updated overview of recent research on NIHL in humans published between 2023 and 2025.

A literature search was performed using the Web of Science Core Collection, employing the term “Hearing loss, Noise-induced” across all fields. This search identified 570 publications (169 from 2023; 222 from 2024; 179 from 2025). Studies were eligible if they were original research conducted in human populations. Reviews, editorials, non-peer-reviewed publications, animal or in-vitro studies, articles unrelated to NIHL outcomes, and publications in languages other than English or Portuguese were excluded.

After applying these criteria, 478 articles were screened. A general analysis of the WOS database showed that the main areas in which the 478 papers were published were Otolaryngology (13%), Neuroscience (11%), Public, Environmental and Occupational Health (11%), Audiology and Speech Pathology (10.5%), and Multidisciplinary Sciences (6%). Most of these were conducted in China (25.5%) and the United States (23.5%), followed by India (7%), South Korea (3.7%), Germany (3.4%), England and Turkey (3.2% each), Iran (2.5%), and Canada (2.1%). Another 47 countries also have publications in this area.

Next, titles and abstracts were reviewed using the Rayyan platform, and 112 studies were retained for final inclusion. Given the heterogeneity of study designs, populations, and outcome measures, a quantitative synthesis was not performed.

The included studies were analyzed using a thematic narrative approach and grouped according to their primary focus, including prevalence and characterization of NIHL, diagnostic and management strategies, unsafe listening practices, biomarkers, predictive models and co-exposures, prevention strategies, and tinnitus, balance disorders, and hidden hearing loss.

Within each theme, findings were summarized and critically discussed, with emphasis on methodological advances, emerging trends, and gaps in knowledge. The objective was not to exhaustively compare individual studies, but rather to highlight key developments shaping current research and practice in NIHL.

RESULTS

Regarding the 112 retained studies, they were categorized according to the primary theme of the objective (Figure 1).

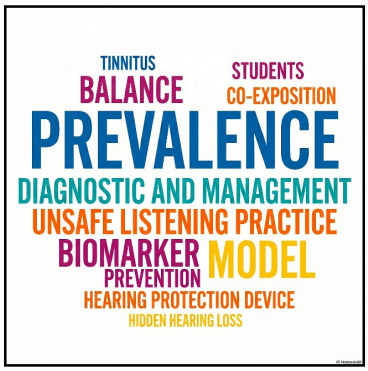

Figure 1: Word cloud overview of the main thematic areas addressed in the included studies. Source: generated by Google Notebook LM on April 29, 2026.

As illustrated in Figure 1, the included studies cluster around several major thematic areas, which structure the presentation of the results in the following sections.

Prevalence and Characterization of NIHL

The prevalence of NIHL varies between countries and sectors. In steel mill workers, the prevalence reached 47%, with tinnitus being an independent predictor of NIHL [4]. In the textile and weaving sector, rates ranged from 14.5% to 71.6%, being associated with lower levels of education and longer working hours [5,6]. In the food industry, rates reached 32.5% to 42.7%, showing an association with length of service and smoking [7,8].

In aviation workers, a significant worsening of hearing thresholds was observed with increasing age and flight hours [9], as well as left ear inferiority in military pilots [10]. Flight engineers were also identified as a risk group for NIHL [11]. Special forces police officers presented significantly higher hearing thresholds than healthy men [12]. Among military dog handlers, compared to other members of the armed forces, the highest incidence rate of NIHL and tinnitus was observed [13]. In a cohort study with police officers, a 2.19 times greater risk of NIHL was found compared to administrative staff [14].

In agricultural workers, tractor operators, and heavy vehicle drivers, rates ranged from 29% to 50%, being more pronounced in the left ear [15-18]. Short sleep duration and long work shifts were identified as predictors of NIHL [15]. Bus drivers presented mild HL, even after 10 years in the profession [19].

The prevalence of NIHL reached 7.6% in airport employees and 51.4% in vector control/fogging workers [20,21]. In comparison with control groups, higher hearing thresholds were observed among call center operators [22], as well as among car wash workers, who are exposed to noise, chemical components, and vibration [23].

A cohort study including various occupational categories showed that longer-term occupations and the risk of cardiovascular disease were associated with worse hearing thresholds, as were age and sex, especially among individuals who reported noise exposure [24].

An epidemiological study conducted between 2006 and 2022 revealed a significant increasing trend in NIHL cases over the period (21.9%), followed by stabilization in the number of cases. NIHL occurred predominantly in manufacturing industries, among men, individuals aged 40 to 49 years, and those with more than 5 years of occupational noise exposure [25].

Regarding non-occupational exposure, the prevalence of NIHL among medical students using headphones was approximately 33% [26]. Among children diagnosed with NIHL, the main correlated factor was prolonged headphone use (approximately 82%), followed by playing musical instruments without hearing protection (approximately 10%). Young musicians presented subclinical damage assessed by distortion product otoacoustic emissions [27].

A study conducted with industrial workers showed that individuals with NIHL exhibited increased aggressiveness, as well as reduced quality of life [28]. In children, NIHL was associated with emotional symptoms [29]. NIHL also demonstrated an association with daily life health conditions and occupational health problems, especially for those who did not use hearing protection [30]. NIHL also showed an association with early cognitive impairment; however, there is no evidence to indicate that NIHL is a mediator of this association [31]. Another study suggested that NIHL may cause alterations in brain function in areas linked to emotion, decision-making, and social cognition, involving a complex process of plasticity [32].

Diagnosis and Management of NIHL

In the diagnostic domain, electrophysiological and artificial intelligence–based methods demonstrated high sensitivity. Chang et al. [33] identified that patients with NIHL exhibit significantly reduced amplitudes of waves I and V on the Auditory Brainstem Response test, suggesting that these measures are robust indicators even in cases of mild HL. Additionally, another study highlighted that neural network–based methods, such as multi-layer perceptrons, show maximal sensitivity for diagnosing NIHL in military personnel, outperforming traditional techniques [34]. Other useful tools include the Level-Specific CE-Chirp stimuli, which were identified as superior to the conventional click for estimating hearing thresholds [35], and the Quick speech-in-noise test, which was validated as a rapid screening tool due to its strong correlation with high-frequency pure-tone audiometric thresholds [36]. In addition, middle ear muscle reflex (MEMR) strength was identified as a sensitive marker for detecting early damage (cochlear synaptopathy) in workers whose hearing remains within normal limits [37].

The analysis of risk factors and the prediction of HL also occupy a central role in management strategies. The duration of employment, particularly beyond five years, and the presence of tinnitus are significant predictors of NIHL development [38]. The nature of the noise further influences the severity of damage; it was shown that impact/impulse noise tends to cause more frequent and severe HL than continuous noise [39]. In the field of artificial intelligence (AI)–based prediction, using AI algorithms, models built using continuous variables such as age and noise exposure dose have provided superior accuracy in assessing individual worker risk [40].

Despite promising diagnostic performance, most AI-based tools remain confined to research settings, with limited validation in routine occupational health practice.The management of at-risk individuals extends to specific occupational groups that often underestimate sound exposure. It was found a prevalence of HL of 84.5% among bartenders, associated with years of professional activity and the lack of protective equipment in environments where noise levels exceed 104 dBA [41].

Finally, NIHL management involves both understanding systemic impacts and assessing the economic feasibility of interventions. Using functional magnetic resonance imaging, one study [42] found that HL alters connectivity within neural networks related to executive and emotional control, which may explain functional impairments following long-term NIHL. From a public health perspective, Bakit et al. (2025) emphasize the importance of preventive strategies, showing that investment in protective measures for workers, such as artisanal fishers, results in significant public cost savings compared with the medical expenses associated with established NIHL [43].

Unsafe Listening Practices

The topic of unsafe listening practices addresses the risks associated with the development of NIHL, as well as the onset of tinnitus and balance disturbances resulting from exposure to high sound pressure levels (SPLs) in recreational contexts, particularly among young people. Knowledge of these risks is often inadequate; one study conducted in South Africa showed that only 9.7% of undergraduate students reported feeling well informed about NIHL, highlighting a high prevalence of potentially unsafe listening behaviors and low NIHL awareness [44]. Similarly, despite exhibiting a positive attitude, medical students have

significant conceptual gaps, such as believing that NIHL is a reversible condition, highlighting the importance of educational interventions to raise awareness among this population. This limited risk perception is further reinforced by Mokhatrish et al. [45] and Rao & Rajashekhar [46], who identified low levels of knowledge regarding early signs of NIHL among Saudi youth and traditional artists in India, respectively. Moreover, young people in the United Kingdom reported considering NIHL as more severe than tinnitus. The authors concluded that the perception of susceptibility and severity of NIHL and tinnitus showed a positive effect on behavioral intentions, which can be used as a strategy for noise-induced hearing loss prevention campaigns [47].

With regard to the use of Personal Listening Devices (PLDs), prevalence rates are alarming. One study reported that 98.7% of young people use headphones daily, in addition to other risky behaviors for NIHL [48]. The impact of these practices is evidenced by another study, which found 17.6% mild sensorineural HL and 32% of a 4kHz notch among young users, associating the damage with prolonged use of in-ear headphones [49]. Gottfriedová et al. [50] corroborated these findings by showing that listening to music for more than seven hours per week significantly alters hearing thresholds. In addition, higher prevalence of HL among individuals who use volumes exceeding 80% of maximum capacity was observed [51]. Although there is no association between HL and prolonged exposure to high SPL, a trend was observed: participants with HL spent more time using headphones than those without hearing loss [52].

The consequences of these practices extend beyond hearing and may affect the vestibular system. Among PLD users, 34.3% experienced symptoms such as dizziness and imbalance, with higher risk observed among those using in-ear models [53]. Another study [54] further showed that headphone users presented ultra-high-frequency HL, as well as signs of saccular (balance) damage even before any changes are detected in conventional audiological tests.

Other leisure activities also pose elevated risks; it was found that 73.4% of nightclub attendees report permanent auditory symptoms [55], and hazardous noise levels in arcades (ranged from 83.05 to 89.4 dBA), where most young people disregard the dangers of high SPL exposure [56].

To mitigate these risks, educational programs and emerging technologies have been developed. Formal educational interventions have proven to be effective in positively modifying awareness, intentions, and attitudes of young people with respect to exposure to high SPLs [57]. From a technological perspective, Turchet et al. [58] tested wristbands with visual and tactile alerts for excessive sound levels and concluded that, while the technology is effective for notification, self-protective action depends largely on the user's prior motivation and attitude. On a social and legislative level, Kaspar et al. [59] reported a demand for greater regulation, with 61.2% of university students advocating for stricter societal control of sound levels. However, Upreti et al. [48] emphasize that despite awareness of the risks, only 25.8% of young people actually use hearing protection, underscoring the need for strategies that translate knowledge into genuine behavioral change.

Biomarkers

Whole-exome sequencing identified the VWF gene as a novel susceptibility marker, exhibiting a high mutation frequency in individuals with NIHL and being primarily expressed in the spiral ligament [60]. Furthermore, variants in the TAOK1, TMTC4, and CNTN1 genes were significantly associated with NIHL [61]. Single nucleotide polymorphisms (SNPs) were significantly associated with the risk of NIHL (CDH23, FAS, GJB2, PTPRN2, SIK3) and may be predictors of NIHL susceptibility, increasing the probability by up to 10 times [62]. Furthermore, the ATP6V1B2 gene (C allele of rs11204100, G allele of rs10503675) showed an association with lower susceptibility to NIHL [63].

Reduced methylation levels in the ATP6 and CYB genes were observed in patients with NIHL, with the CYB gene identified as a biomarker with high diagnostic sensitivity [64]. Another study investigated the microRNA (MiRNA) profile in NIHL, detected in peripheral blood; for example, hsa-miR-486-2 showed a significant increase and hsa-miR-6723, a reduction, reflecting

apoptosis processes and mitochondrial instability resulting from cellular stress [65]. Serum proteomics (IGFBP2, ZYX, CKM, and CFHR4) also demonstrated high predictive capacity for the risk of NIHL [66].

Exposure to noise triggers a cascade of molecular damage that can compromise DNA integrity and cellular function. A correlation was observed between noise exposure time, degree of HL, and percentage of DNA damage in textile industry workers [67]. Other authors have found that the absence of the GSTM1 gene (null genotype) and low serum GST enzyme activity significantly increase susceptibility to NIHL [68]. Furthermore, low levels of the HO-1 protein and polymorphisms in the hOGG1 and GPx-1 repair genes were associated with the presence of notches in the audiometry of noise-exposed workers [69].

Regarding neuroimaging exams, workers with NIHL present greater cortical thickness in the inferior parietal gyrus and increased surface area and cortical volume in the occipital lobe, suggesting that hearing deprivation leads to a restructuring of auditory-visual networks [70]. Connectivity networks were also assessed and revealed an abnormal topology in the brain, with reduced efficiency in the right medial orbitofrontal gyrus [71], as well as in other areas [72]. Damage to the white matter microstructure was also observed, particularly in the fibers connecting to auditory and language areas [72]. Furthermore, PET-CT images showed glucose hypometabolism in the superior temporal gyrus and insula, which may reflect the effects of NIHL [73].

Models and co-exposure

The integration of advanced algorithms has demonstrated superior diagnostic and predictive capabilities compared to traditional methods. Among other analyses tested, the support vector machine (SVM)-based algorithm, using magnetic resonance imaging data, achieved 95% accuracy in identifying individuals with NIHL [74]. Another model based on the use of multilayer perceptrons also showed high sensitivity (0.986) and specificity (0.902) in identifying this condition in military personnel [75]. The XGBoost algorithm stood out in risk prediction using blood and biochemical indicators [76] and in classifying damage caused by different types of noise [77]. Additionally, the algorithm based on Decision Trees integrated into wearable devices allowed real-time monitoring of miners with 91.25% accuracy [78]. The asymmetric convolution model outperformed the predictions made by the 1999 ISO prediction model as well as the SVM, as it combined complex characteristics (time-frequency) and personal information [79]. An artificial neural network was also used to predict noise and personal information to predict NIHL, based on hearing thresholds up to eight years, revealing a discernible trend [80].

Models including kurtosis adjustments have shown promise. Increased kurtosis levels, for both complex and impulsive noise over prolonged periods (over 10 years) (vs. steady state), suggest that currently practiced tolerance limits based solely on cumulative noise exposure may be insufficient for NIHL prevention [81-84] and that without kurtosis adjustment, the risk of NIHL may be underestimated by approximately 9.5% to 11.2% [85]. Furthermore, it appears that with increasing kurtosis, the audiometric notches become deeper, shifting to frequencies between 1 and 3 kHz in cases of complex noise [81]. Furthermore, combined exposure to noise and dust has demonstrated a synergistic effect on NIHL [86,87].

Genetic and biological indicators, such as SNP loci, serum albumin, and creatinine, can improve the predictive accuracy of models, contributing to risk stratification for NIHL [76,88,89]. Similarly, incorporating information related to lifestyle, comorbidities, noise exposure levels, and co-exposure to additional occupational hazards, such as vibration or dust, may further enhance predictive performance [87,90].

Individual susceptibility can determine more significant HL. Therefore, it is important to develop models that identify parameters to stratify this variable. For example, hearing thresholds at frequencies of 4 and 12.5 kHz showed the best performance in detecting this increased sensitivity [91]. Additionally, temporary threshold shift (TTS) monitoring has proven to be a valuable tool for identifying increased susceptibility to NIHL, as well as for guiding hearing protection policies [92].

Prevention of NIHL and Hearing Protection Devices

A study evaluating websites on NIHL prevention in both English and Spanish found that their reading levels were excessively complex for the general public, although the Spanish-language websites demonstrated superior quality [93]. Another study found that participants demonstrated a high level of basic awareness that noise can be harmful; however, important gaps remain regarding safe exposure time and intensity, with social media identified as the primary source of information [94].

Regarding knowledge, risk perception, and attitudes toward noise, university students reported not feeling vulnerable to permanent damage due to exposure to amplified music and facing social barriers to the use of HPDs [95]. On the other hand, attendees of electronic music events tended to use HPDs more frequently, preferring high fidelity HPDs, and reported being influenced in their attitudes by social media, a strategy that can be used to increase HPDs use for other groups [96].

A study with miners found positive attitudes toward HPDs and the prevention of NIHL, but the physical discomfort caused by HPDs remains a barrier [97]. Maintenance workers, on the other hand, demonstrated greater knowledge about noise and the signs of NIHL when compared to administrative staff. However, less than half of them reported being unable to use HPDs effectively without training, and only a small percentage (less than 15%) suggested that training for the use of HPDs is necessary. These results may reflect a lack of training in the workplace, as 88% of them had never received it [98].

The physical discomfort caused by HPDs was evaluated in field tests with different models over 7 weeks. This study identified that the radial force of the HPDs, the extraction force, and the coefficient of friction influence physical comfort, in addition to the characteristics of the work and the individual [99]. A behavioral intervention aimed at increasing the use of HPDs was carried out through motivational telephone interviews with agricultural producers; there was a marginal increase in the frequency of use after the intervention, but more research is needed on the subject [100].

Another study found that cumulative noise exposure, adjusted for the personal attenuation rate (PAR) of the HPD, can more accurately represent the level of noise exposure, showing an apparent dose-response relationship with the prevalence of NIHL [101].

Regarding new therapies, hyperbaric oxygen therapy has been shown to be more effective than conventional treatment for NIHL in a 12-month follow-up, considering hearing thresholds and the incidence of symptoms (including tinnitus) [102]. On the other hand, the application of infrared light before noise exposure did not cause a significant protective effect in mitigating noise-induced TTS in humans [103].

HPDs were also addressed. A "dynamic ear protector" was developed with the aim of filtering high-frequency noise while amplifying speech frequencies (up to 13 dB) and was evaluated by participants during an 8-hour shift, showing good acceptance and promising results [104].

Regarding hearing conservation programs, a study with four companies aimed to analyze the costs. It was found that none of them includes cost analysis in their risk assessments and that the largest expense was related to the purchase of HPDs, while audiometry represented the lowest cost [105].

A study conducted with metalworkers from 2003 to 2018, who participated in the company's hearing conservation programs, found an increasing trend in NIHL, although with low percentage variation. Despite not showing a stationary trend, the authors emphasized that the rate of evolution of NIHL did not follow what was expected for a population exposed to noise, suggesting that properly implemented hearing conservation programs can mitigate NIHL [106].

Tinnitus, Balance, and Hidden Hearing Loss (HHL)

Tinnitus manifests itself not only as an annoying symptom, but can be useful as a biomarker. One study showed that individuals with NIHL had higher hearing thresholds and greater

tinnitus intensity, as well as lower otoacoustic emission response rates and prolonged auditory brainstem response (ABR) latencies, compared to other HL etiologies [107]. Another study highlighted the relevance of this symptom, supporting a vector machine model and potentially increasing the success of occupational health and safety programs, since tinnitus was the second most important indicator for predicting NIHL, surpassed only by age [108].

A Population-based study indicates that the prevalence of tinnitus is more than twice as high in individuals with NIHL compared to those with age-related HL [109]. In addition, it was found that this condition might disproportionately affect specific populations, such as dental professionals, among whom up to 40% report experiencing tinnitus [110].

Using physiological measures (ABR, MEMR, envelope following response), a reduction in the magnitude of neural responses was found in veterans exposed to noise with normal audiogram and tinnitus, suggesting that cochlear synaptopathy may contribute to the perception of tinnitus, resulting in damage equivalent to approximately 20 years of natural aging [111].

Vestibular function is also vulnerable to exposure to high SPLs, which can lead to dizziness or dysfunctions that may occur in a hidden way. Firefighters exposed to noise have been shown to have "hidden vestibular loss," characterized by reduced amplitudes and higher vestibular evoked myogenic potential (cVEMP) thresholds, even in the absence of evident symptoms of dizziness or HL, when compared to matched controls [112]. Similarly, young headphone users may present early saccular damage, evidenced by reduced cVEMP amplitudes, despite having normal audiograms [54]. In industrial settings, textile workers with NIHL showed significantly higher rates of abnormalities on video head impulse test (vHIT) (40%) and caloric tests (33.3%) compared to control group [113]. In Brazil, the prevalence of dizziness among individuals with NIHL reached 23.4% and was associated with factors such as female sex, hypertension, tinnitus, and continuous noise exposure [114]. The concomitant impairment of auditory and vestibular functions is further confirmed by another study that showed significantly higher VEMP thresholds in NIHL group [115].

HHL and cochlear synaptopathy are related to alterations in neural connections that can impair auditory function without, however, altering conventional pure-tone audiometric thresholds. Dental prosthesis students, divided into high- and low-risk groups according to their noise exposure score, were evaluated and showed signs of HHL: lower otoacoustic emission suppression values in the high-risk group, as well as a decrease in the amplitude of wave I of the suprathreshold ABR with mask, compared to the low-risk group, despite normal threshold limits in the audiogram [116]. Another case-control study aimed to evaluate procedures for identifying this condition in individuals with normal audiograms, including behavioral tests (speech intelligibility in noise test - SPIN, gaps detection in noise, and pitch pattern sequence test) and electrophysiological measures (ABR and electrocochleography - EcochG). Results showed that the SPIN, as a behavioral test, and the EcochG, as an electrophysiological test, provided the greatest auditory diagnostic capability for identifying HHL [117]. Evidence that synaptic damage accelerates auditory impairment in a manner comparable to prolonged biological aging reinforces the need for the creation of clinical protocols for the early detection of HHL in exposed populations [111].

DISCUSSION

NIHL remains a major global occupational and public health concern, despite decades of preventive regulations, technical standards, and educational efforts. Recent epidemiological evidence consistently shows that NIHL persists across a wide range of occupational sectors and recreational contexts, with stable or even increasing trends, particularly in low-income and rapidly industrializing countries [1,3,25]. These findings indicate that existing regulatory frameworks and hearing conservation programs have not achieved the expected impact in the real world. This gap between knowledge, public policies, and the effectiveness of preventive actions underscores the need for a critical reassessment of noise exposure limits [81-84] and how prevention strategies are implemented and managed in practice.

In addition, another challenge highlighted by recent research is that NIHL is not a uniform condition. The substantial interindividual variability in susceptibility, driven by genetic and biological factors as well as situational ones, is reflected in different audiological profiles, even with similar noise exposures [60-69]. This growing body of evidence emphasizes the need for reflection on the continued reliance on universal exposure limits, which assume homogeneous biological responses, and on the need to include individual characteristics in risk prediction models, aiming for a better fit of preventive measures.

In addition, it is essential that other changes resulting from noise exposure, besides NIHL, be considered and incorporated into hearing conservation programs. Tinnitus, HHL, vestibular dysfunction and/or central auditory dysfunction may precede NIHL [107-111], causing impairments in communication, balance, cognitive function, mental health and quality of life [28-32]. These subclinical and functional manifestations challenge the traditional diagnostic and medico-legal definitions of NIHL and suggest that current surveillance systems underestimate the true impact of noise exposure on health.

Advances in predictive modeling further reinforce this concern. Studies including kurtosis adjustments, co-exposures, and other approaches have suggested that currently practiced tolerance limits based solely on cumulative noise exposure may be insufficient for NIHL prevention [81-84], as they underestimate the biological risk [43–46].

The observed landscape of NIHL reflects not only technical limitations and gaps that still exist in knowledge, but also behavioral, social, and organizational barriers. High levels of awareness about the risk coexist with low adoption of protective behaviors, emphasizing that effective prevention requires the integration of technological solutions with behavioral science and ergonomics, as well as interventions at cultural and political levels [48,57-59], aiming at paradigm shifts.

Finally, scientific advances in innovative therapies were observed [102,103], which, although still under study, show the potential of such methods in the prevention and mitigation of NIHL.

CONCLUSION

NIHL remains a prevalent yet largely preventable condition, affecting individuals across occupations and leisure settings worldwide. Recent literature (2023–2025) highlights that, despite increased awareness and technological advances, the global burden of NIHL has shown limited reduction, exposing persistent gaps in prevention and risk management.

A key advance in the field is the growing recognition of individual susceptibility, complex noise characteristics, and subclinical damage, supported by progress in artificial intelligence, biomarkers, and neuroimaging. These approaches offer promising opportunities for earlier detection and improved risk prediction, but most remain insufficiently translated into routine clinical and occupational health practice.

Overall, effective reduction of NIHL will require integrated strategies that combine precision-based diagnostics, improved hearing conservation programs, behavioral and educational interventions, and public policies that better account for noise complexity and co-exposures.

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Noise as a Public Health Problem

Noise outcomes from HSE health-focused inspections April 2024-November 2025

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ABSTRACT

The Health and Safety Executive (Great Britain's national regulator for workplace health and safety) has completed the first phase of an inspection programme of a wide range of industries looking primarily at four health topics including noise. The noise aspects of the first phase of the programme focused on the provision and use of hearing protection and health surveillance for noise induced hearing loss. An initial analysis of the trends in the findings is presented focusing on the provision, selection, use and management of hearing protection where workplace noise has been found to be a problem. 97% of visited workplaces provided hearing protection to workers who need it with basic passive earplugs and earmuffs making up the majority of what was provided. Almost 20% of workplaces made no assessment of the suitability of the hearing protection they provided and 95% of workplaces made no assessment of the audibility of essential communications or warning alarms/sounders for workers who wear hearing protection. Provision of some hearing protection appears to be becoming regular custom and practice in noisy workplaces in a similar way to how provision of hard hats has become on construction sites. However, there are more nuances in the choice of hearing protection than hard hats and this is not accounted for in a significant number of workplaces.

INTRODUCTION

The Health and Safety Executive (HSE) is Great Britain's national regulator for workplace health and safety. HSE ran a proactive health-focused inspection campaign inspecting a range of industries between April 2024 and March 2026. Exposure to noise is one of the health topics. This paper presents the hearing protection specific noise outcomes from 3456 of these inspections for the 20-month period from April 2024 to November 2025.

GREAT BRITAIN'S NOISE LEGISLATION

Great Britain's occupational noise legislation is the Control of Noise at Work Regulations 2005 [1] (CNWR). The regulations define action and limit values for noise exposure. For continuous noise, they are defined as 8-hour or 40-hour equivalent average noise levels for daily or weekly exposures respectively. They are known as daily or weekly personal exposure levels ($L_{EP,d}$ or

$L_{EP,w}$). $L_{EP,d}$ corresponds with $L_{EX,8h}$ as defined in ISO 1999 [2]. Table 1 gives the values in dB(A) $L_{EP,d}$ and $L_{EP,w}$ for the exposure action and limit values.

Table 1: United Kingdom noise legislation exposure action and limit values

	Exposure – dB(A) $L_{EP,d}$ or $L_{EP,w}$
Lower Exposure Action Value (LEAV)	80
Upper Exposure Action Value (UEAV)	85
Exposure Limit Value (ELV)	87

If employees are found to have noise exposures at or above the UEAV then the regulations trigger duties including the requirement to reduce exposure, provide hearing protection, implement health surveillance and provide information, instruction and training.

INDUSTRIES AND WORK INSPECTED

The health-focused inspections concentrated on the manufacturing and construction industries. Other industries covered include utilities companies, agriculture, forestry, motor vehicle repair and waste and recycling.

In the first 20 months of the campaign, 13828 inspections were made. Of those, 3456 (25%) were judged by the inspectors to be to sites where noise exposures were likely to be above the UEAV. Figure 1 shows the percentage of sites where noise exposures were likely to be above the UEAV broken down by industry.

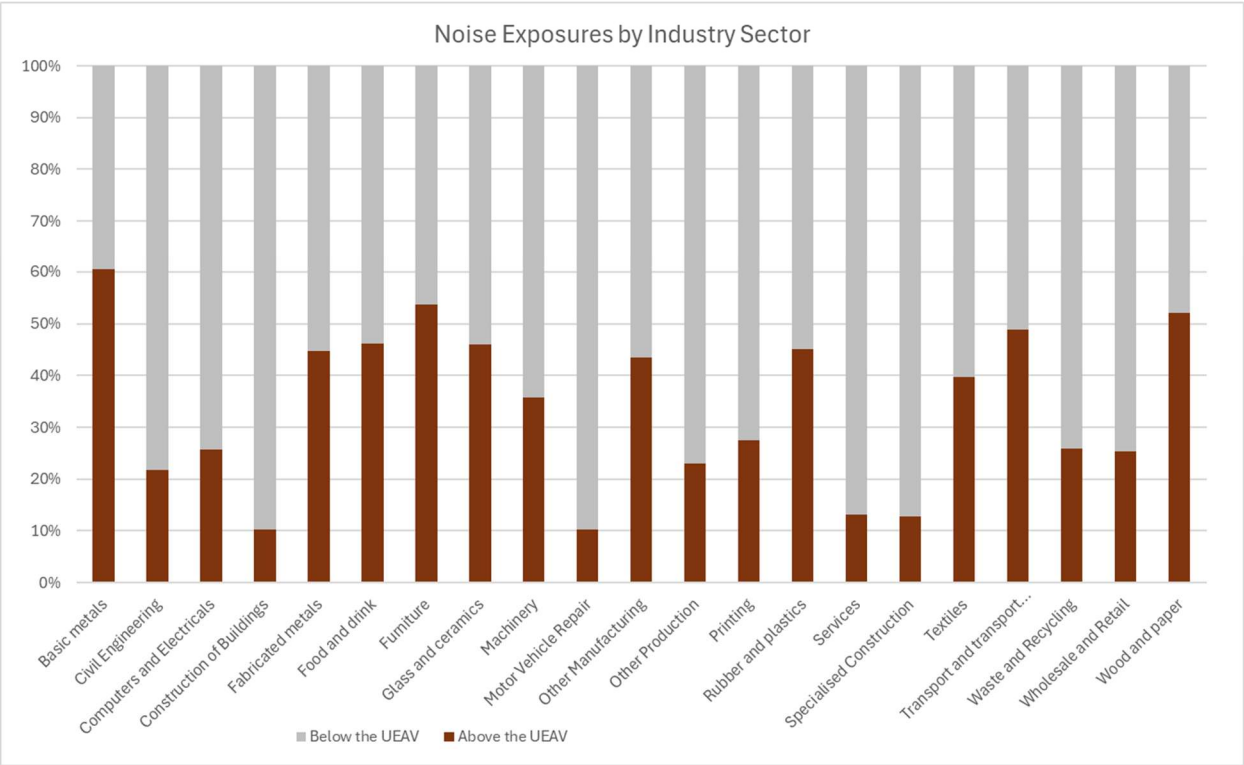

Figure 1: Percentage of sites where noise exposures were likely to be above the UEAV.

Previous HSE work on real world use of hearing protection

A study reported in HSE research report RR720 [3] explored similar areas to this paper in 2009. In that study, 15 employers were interviewed regarding hearing protection use at their premises. 13 of those employers allowed observations of hearing protection use to be made at their premises.

This paper gives data from 3456 sites rather than 15, however, it was not possible to go into as much detail behind the reasoning behind the hearing protection choices made at each site.

The 15 sites involved in the RR720 study did so voluntarily and appointments were made for the site visits. The 3456 sites visited that are reported in this paper were inspected unannounced.

QUESTION TOPICS BEING RECORDED FROM INSPECTIONS

When recording each inspection, Inspectors were asked to complete a series of questions concerning hearing protection selection, provision, training and use. The questions were designed to produce easily analysable statistics that can be broken down by industry.

It was not possible, during the inspection campaign, to explore the reasons each individual site had for assessing hearing protection requirements in the way that they did or for their choice of hearing protection types.

Provision of Hearing Protection

Questions covered:

a. Types of passive hearing protection provided, if any at all.
b. Types of electronic hearing protection provided, if any at all.

Passive hearing protection includes broad categories such as ear plugs, ear muffs and custom moulded ear plugs.

Risks from overprotection

Overprotection occurs when hearing protection attenuates noise so that the noise level underneath the hearing protection is less than 70 dB(A). This occurs when the hearing protector has too much attenuation for the noise being protected from.

Workers who are overprotected may:

a. Fail to recognise warning alarms and signals
b. Misunderstand essential communications
c. Feel isolated from their working environment

Low attenuation hearing protection, which may alleviate overprotection, can be difficult to find. A rule of thumb guide to choosing hearing protection with suitable attenuation to adequately protect from noise while avoiding overprotection is published in the HSE guidance document L108 [4]. The rule of thumb allows hearing protection to be selected via its single number rating (SNR) and only A-weighted noise information. The information in the rule of thumb is intended as a guide rather than a substitute for using one of the standard methods for calculating expected at-ear noise levels, and in particular will not be appropriate if there are significant low-frequency components to the noise in question. Table 2 is a reproduction of that rule of thumb.

Table 2: Rule-of-thumb guide to selecting hearing protection from HSE L108

A-weighted noise level (dB(A))	Select a protector with an SNR (dB) of…
85-90	20 or less
90-95	20-30
95-100	25-35
100-105	30 or more

Some industries, such as the food and drink industry, require that hearing protection is either metal or x-ray detectable. This can further limit their choice of hearing protection such that overprotection is unavoidable.

The potential risks caused by overprotection in a workplace is high if any of these factors apply:

a. Safe working is dependent on easy verbal communication between workers.
b. Safe working is dependent on warning alarms and sounders being sufficiently audible to attract attention.
c. Safe working is dependent on being able to easily hear process related/generated noises that may indicate an unsafe condition.
d. There is the potential for workers and vehicles to be operating in the same area.
e. There are noise exposed hearing aid wearers and/or workers with hearing loss.

The potential risks caused by overprotection in a workplace is low if none of the high risk factors apply.

Electronic Hearing Protection

Electronic hearing protection includes:

a. Sound-restoration or level-dependent hearing protectors
b. Hearing protectors with entertainment audio input
c. Hearing protectors with work or safety-related audio input

Only electronic functions that directly affect risk positively or negatively were included. Active noise reduction hearing protectors were not included as the electronic systems in those hearing protectors enhance the low-frequency attenuation rather than add any additional functions.

Sound-restoration level-dependant hearing protectors can help mitigate the risks from over-protection by allowing easier communication and easier hearing of warning alarms or shouts than when wearing passive hearing protection.

Hearing protectors with entertainment audio input allow the wearer to listen to music or radio while having their hearing protected. The level of the replayed entertainment signal should be limited to 82 dB(A). The replayed music/radio can decrease the audibility of communication or warning alarms/sounds as they have to compete with the noise in the environment, the attenuation of the hearing protector and the music/radio being replayed. This reduced audibility can increase safety risks.

Hearing protectors with work or safety-related audio input will replay those signals without any limit on the volume setting. There is therefore the potential for increased noise exposure if volume settings are not carefully controlled. However, these systems can aid in safety critical communications and audibility and reduce the likelihood of overprotection causing safety risks.

The CNWR [1] require that hearing protection is used by employees whose noise exposures are likely to exceed the UEAV. That hearing protection must eliminate the risk to hearing or reduce the risk to as low a level as is reasonably practicable. There is no requirement to use any particular type of hearing protection. It is likely that a range of hearing protection may have to be offered to a workforce to account for different noise environments, compatibility with other PPE and to suit each individual.

Hearing Protection Suitability

Attenuation Selection Methods Used

For both continuous and impulsive noise, standard methods for calculating likely at-ear noise levels are defined in BS EN ISO 4869-2 [5]. For continuous noise, HSE has produced a calculator [6] which uses the standard methods. These standard methods require either A and C-weighted noise data (usually an L_{Aeq} and an L_{Ceq}) or octave-band frequency data along with the appropriate attenuation data for the hearing protector.

The same rule of thumb guide to choosing hearing protection as detailed above can also be used for when C-weighted or octave-band noise data is not available. This method does not calculate likely at-ear noise levels but does give a guide to choosing hearing protectors with an appropriate SNR. It is not suitable for use in environments with significant amounts of low-

frequency noise. This method only requires A-weighted noise data. The guide has been reproduced from the HSE guidance document L108 [4] in Table 2.

Checking For Overprotection Issues

Where overprotection is unavoidable then functional checks are advised to determine if workers who need to communicate can do so when wearing the supplied hearing protection. While standard methods are available for selecting suitable auditory warning signals (for example, BS EN ISO 7731 [7]) which take into account the use of hearing protection, simple in-situ listening tests can be the most effective way of ensuring that workers can hear necessary communications, alarms and warnings. It is not sufficient to be able to hear an alarm or warning while listening for it, it must be audible enough for it to attract attention over any background noise. These checks will likely have to be performed for all workers as each worker will have a different hearing ability.

Use of Hearing Protection

Hearing protection is only of any use if it is being worn when and where it is required. It will only be providing the expected performance if it is worn correctly.

Training Provision

Regulation 10 of the CNWR requires that employees who are exposed to noise at or above the lower exposure action value (80 dB(A) $L_{EP,d}$ or 135 dB(C) L_{CPeak}) must be provided with suitable and sufficient information, instruction and training. Paragraph 231 of the HSE guidance document L108 [4] provides a non-exhaustive list of hearing protection related topics that should be provided to employees who are required to wear hearing protection. Questions asked during inspections regarding training were based on this list.

OBSERVATIONS FROM INSPECTIONS

Overall results across all industries are presented in the subsequent sections of this paper. No further breakdown by industry will be provided due to the number of visits made in each industry being only a small percentage of the total number of businesses in each industry. The highest percentage visited was 12.61% for the rubber and plastics industry and the smallest was 0.04% for the wholesale and retail industry. The median percentage visited was 2.90%. Data on the number of businesses in each industry sector was from the ‘UK business; activity, size and location: 2025’ data provided by the Office for National Statistics [8].

All the following reported percentages are of the number of sites visited, not of all sites.

Hearing Protection Provision

102 sites (3%) did not provide any hearing protection to their workers who were exposed to noise at or above the UEAV.

Types Of Hearing Protection Provided

Figure 2 shows the percentage split between types of passive hearing protection and electronic hearing protection of any sort.

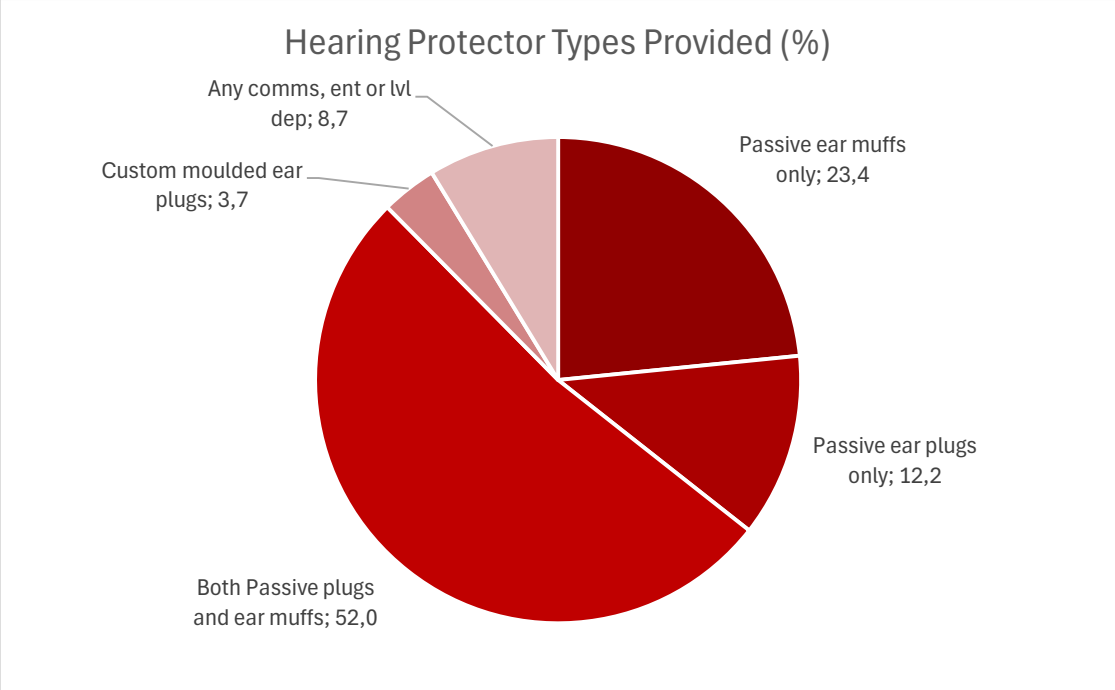

Figure 2: Types of hearing protection provided.

Passive Hearing Protection

87.6% of sites provided passive ear plugs, ear muffs or both to the workers. At the time of writing (March 2026), standard (non-custom moulded) passive hearing protection offers little choice for SNR values at or below 20 dB.

For SNR values above 20 dB, this category offers the widest choice in terms of form factor and sizes. This maximises the likelihood that hearing protection can be found that fits the individual and is compatible with any other PPE and headgear that is being worn. This combined with widespread knowledge of their existence and their relative low cost may explain why this is the dominant category of hearing protection being offered.

Electronic Hearing Protection

8.7% of sites visited used electronic hearing protection of any type. Not every site will benefit from the use of electronic hearing protection. It is not possible to establish, from this inspection data, how many of the sites inspected could benefit from electronic hearing protection.

For sites that could benefit, potential reasons for not supplying them could include a lack of awareness of either their existence or their potential benefits. Even with that knowledge, the extra cost over passive hearing protection may also be a significant factor in how little use electronic hearing protection gets.

Custom Moulded Earplugs

Only 3.7% of sites visited were using custom moulded earplugs. The same factors as for electronic hearing protection may be the reason for their relative lack of use in industry.

Custom moulded earplugs are available in lower attenuations than other hearing protection types which may help to alleviate any overprotection risks that standard hearing protection may cause. Other functionalities such as a flatter frequency response are available in custom moulded earplugs.

It was not possible, as part of these inspections, to explore the reasoning behind some employers choosing to offer custom moulded earplugs to their employees.

Hearing Protection Suitability

Figure 3 shows the percentage split of ways that employers have assessed the suitability of the hearing protection they provide. It is possible that some employers will choose more than one option. For example, they may use internal health and safety staff who then use the HSE's calculator to help them choose from a selection of hearing protectors recommended by a hearing protection supplier.

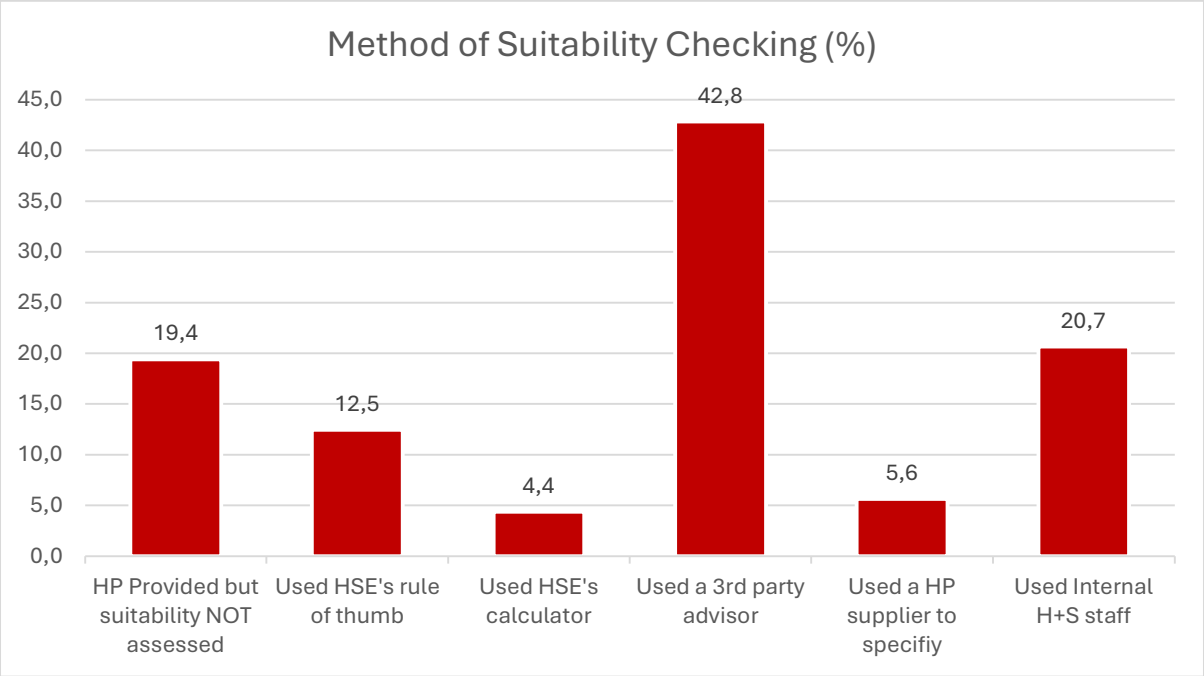

Figure 3: Methods used to assess suitability of hearing protection.

Of the 3354 sites where hearing protection was provided, 19.4% of those sites made no assessment of the suitability of the hearing protection they provided. For these sites, the employer is unlikely to know if the provided hearing protection has suitable attenuation for the noise environment. It could be overprotecting and preventing easy communication or warning alarms or sounds being heard. It might be that individuals are not wearing their hearing protection correctly, or at all, because they find it too difficult to communicate while wearing it.

With regards to identifying potential risks due to overprotection, only 4.9% of sites made any kind of audibility assessment with the hearing protection offered to their employees. Those that haven't made any kind of audibility assessment may have chosen hearing protection with an appropriate level of attenuation but that still does not guarantee that all workers can hear what they need to hear.

Hearing Protection Use

It is likely that a combination of factors will influence whether any particular individual wears their hearing protection at all and whether it is worn correctly. HSE Research Report RR720 [3] discusses real world use and performance of hearing protection in detail including factors that can influence whether hearing protection is worn.

Figure 4 shows that at 87.5 % of sites, workers were observed to be wearing hearing protection when needed. At 86.0% of sites, workers were seen to be wearing hearing protection correctly.

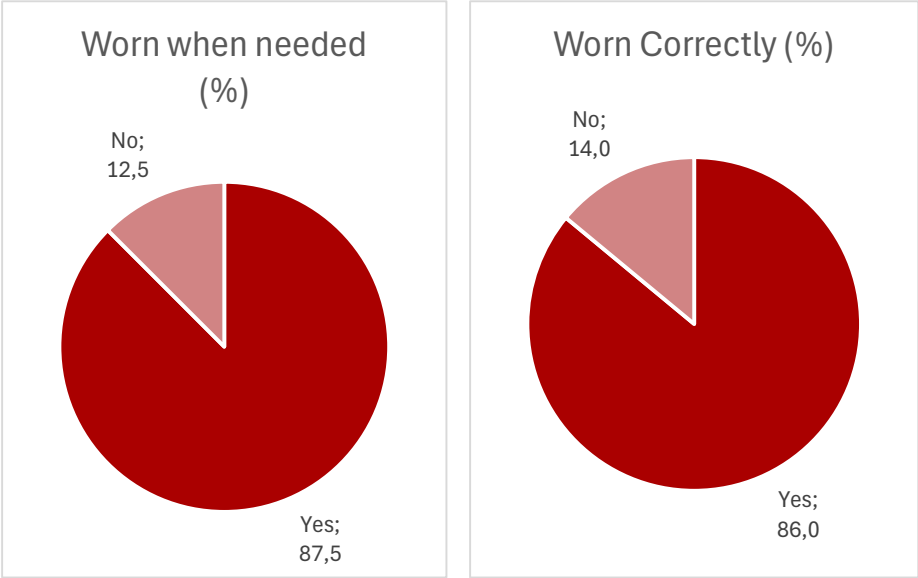

Figure 4: Is hearing protection worn when needed and worn correctly

Is hearing protection being worn when and where needed

RR720 [3] found that across the 15 employers observed, the estimated ratio of workers not using hearing protection was 1 in 7, or 14%. This compares with 12.5% in the current inspection campaign which would appear to be a slight improvement. However, this difference may be explained by the small size of the RR720 study compared with the number of recent inspections. There is also likely to be some uncertainty with the current inspections. An inspector who is inspecting multiple health topics on a large site will not be able to directly observe every worker who should be wearing hearing protection. In the RR720 study, this was possible to achieve.

Is hearing protection being worn correctly

RR720 [3] reported a variation in correct fit by hearing protection type. Compressible foam earplugs were the most likely to be poorly fitted and ear muffs were *"generally but not universally in good condition and properly worn"*.

For this inspection campaign, only overall figures for how well-worn hearing protection of all types is are available. It was not possible to break down the figures by hearing protection type.

Training Provided

RR720 [3] demonstrated that effective employer provided training is important to ensure full and proper use of hearing protection. However, training alone does not guarantee full and proper use of hearing protection.

Figure 5 shows the percentage of sites who have provided training at all and in the topics listed at paragraph 231 of the HSE guidance document L108 [4]. Almost 20% of sites provided no training regarding hearing protection to their noise exposed workers.

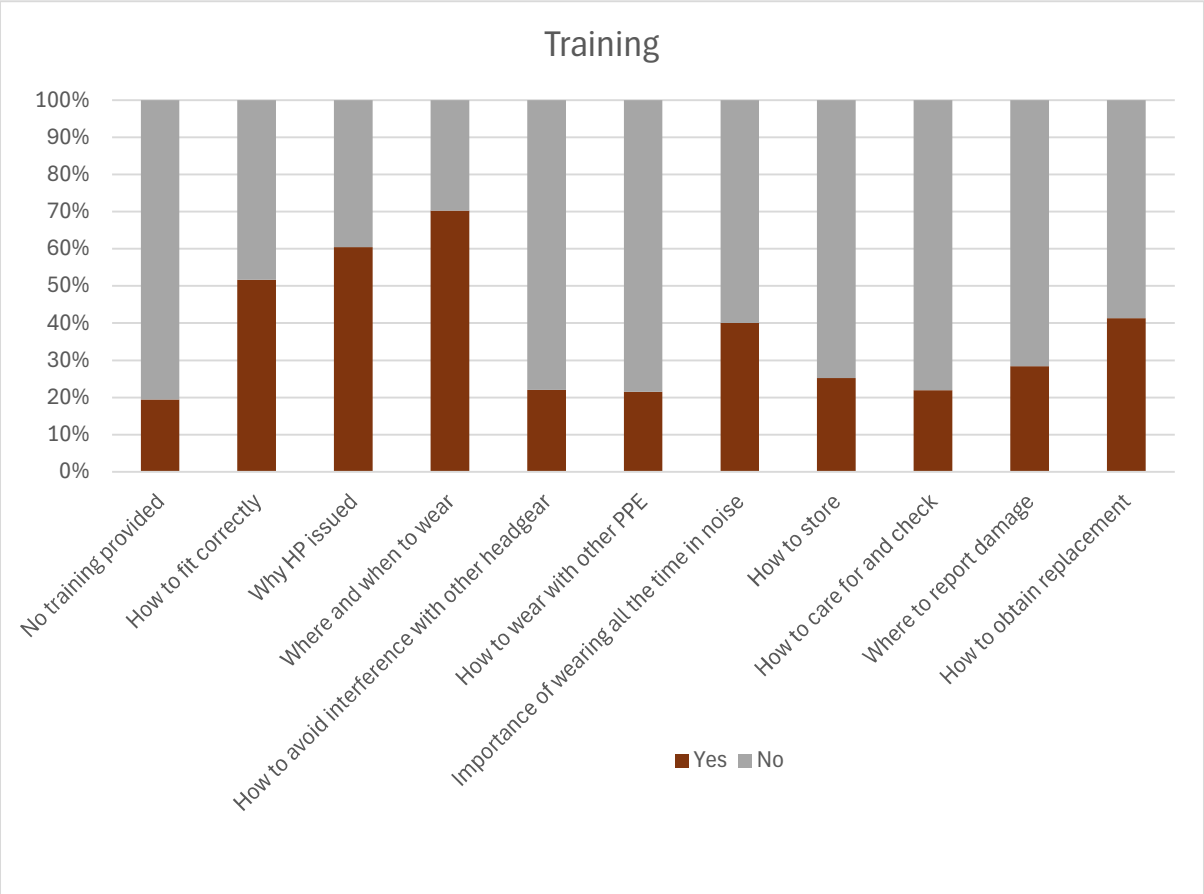

Figure 5: What training regarding hearing protection is provided.

CONCLUSIONS

The first 20 months of inspections have shown that the majority (97%) of, but not all, noisy workplaces provide hearing protection to their noise exposed employees. Most of that hearing protection consists of passive earplugs and earmuffs. Electronic hearing protection is provided at less than 9% of sites and custom moulded earplugs at less than 4% of sites.

Just under 20% of employers do not assess the suitability of the hearing protection they provide. Of those that do assess the suitability, more than 40% follow the advice of a 3rd party. Less than 5% of sites make any assessment of any audibility issues for their employees using the hearing protection they provide.

Approximately 80% of sites provide some training in the use of hearing protection to their workers. The content of that training varies widely. For example, only approximately 50% of sites train their workers on how to fit hearing protection correctly.

ACKNOWLEDGEMENTS

Thank you to all involved with the planning, implementing, administering of the inspection campaign that this paper discusses only a small part of.

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Hearing loss Is not part of normal physiological aging: a critical review of the literature ©

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ABSTRACT

Hearing loss is considered an inevitable result of aging, exemplified by the terms *presbycusis* and *age-related hearing loss*. A critical review of the literature, however, suggests that this is not normal physiological aging but is largely caused by cumulative excessive lifetime exposure to noise, i.e., it is noise-induced hearing loss in elderly persons. Studies done in the 1960s in isolated populations not exposed to excessive noise found that auditory sensitivity was preserved into old age. Occupational studies established the noise doses causing hearing loss. Anatomic studies show that noise exposure causes hearing loss in humans. Animal studies elucidated mechanisms of noise-induced hearing loss down to the cellular, intracellular, and genetic levels, although the physiology of noise-induced hearing loss in older animals may be different from that in humans. Why does this matter? Prevention of disease is better than treatment. Age-related hearing loss is sensorineural hearing loss. Amplification remains the most widely-used treatment for this, but it does not restore normal hearing. If a condition common in old age is inevitable, e.g., thinning gray hair, prevention isn't possible. If it is caused by diet, obesity, inadequate exercise, or exposures, e.g., hypertension, diabetes, heart disease, or skin cancers, perhaps its onset can be delayed or prevented by behavior change. Hearing loss with aging is a disease of civilization that can largely be prevented by reducing noise exposure. The terms *sociocusis*, *noise-induced hearing loss in elderly persons* or the neologism *otoaging* better describe preventable hearing loss in older people.

INTRODUCTION

Hearing loss is defined by the World Health Organization (WHO) as a 25-40 decibel (dB) or greater decrease in the hearing threshold level [1]. Better hearing than that is classified as normal, although truly normal hearing has a 0 dB decrement.[2] A 25-40 dB hearing loss is usually not enough to require hearing aids, but can cause difficulty understanding speech, especially in noisy environments [3].

Hearing loss is thought to be inevitable with age, as exemplified by the widely used terms *presbycusis* and *age-related hearing loss* (ARHL) [4]. ARHL is sensorineural hearing loss, the result of noise damage both to cochlear hair cells and to synaptic junctions between hair cells and the auditory nerve [5]. If the effect of sunlight (UV light) on the skin is called *photoaging*, perhaps a better word to describe both the premature aging of cochlear hair cells and

synapses caused by noise and the end result, hearing loss in old age, is *otoaging*, This neologism will be used in most of this paper.

The biological bases of aging are not precisely known, with many theories of aging based on genetic or biochemical changes in cells and subcellular structures [6]. Regardless of the mechanisms, the effects of aging are readily apparent even to the most casual observer. As humans reach old age, usually defined as 60 or 65 years, men and women gain weight, hair thins and turns gray, skin sags and wrinkles, age spots appear, performance times in running events increase, and hearing gets worse.

Otoaging is common in industrialized nations. In the United States, more than two thirds of adults >60 years of age have some form of clinically significant hearing loss [7]. It is difficult to estimate the prevalence of otoaging in Europe [8] and Japan [9] due to differing study designs, but at least 25-50% of those >65 have hearing loss. These numbers are likely underestimates because screening audiometry is an insensitive measure of auditory damage. More sensitive tests would detect more extensive hearing loss earlier in life.

Is the high prevalence of otoaging in industrialized nations due to normal physiological aging, or does it represent the cumulative effect of a lifetime of excessive noise exposure on the ears? Stated another way, is ARHL really just noise-induced hearing loss (NIHL), otoaging, in elderly persons? That is the question this review attempts to answer, updating an analysis presented at the 12th ICBEN Congress in 2017 [10].

ABNORMAL AGING

Many changes prevalent in older humans once thought to be part of normal aging are now known to be the result of abnormal or pathological aging. Among these are obesity, muscle weakness, diabetes, hypertension, heart disease, and skin cancers. Absent specific genetic syndromes, abnormal aging can be ascribed to four basic causes: 1) exposures, 2) dietary intake, both quantity and composition, 3) disuse atrophy, and 4) suboptimal medical care. Suboptimal medical care refers not to individual patients getting poor quality medical care, but rather to patients collectively receiving standard treatments that are later found to have been suboptimal. Two examples are better treatment of hypertension in elderly persons, leading to fewer strokes and less heart disease, [11] and prevention of edentulism in older persons by improved dental care [12]. Both conditions had been thought to be from normal aging.

Abnormal aging caused by exposures is perhaps most relevant to otoaging. Exposure to various types of energy or to toxic substances can cause premature aging. The best analogy for the ear being damaged by noise exposure may be the skin being damaged by sun exposure. There is no such thing as a healthy tan. Ultraviolet light in sunlight damages the skin by causing changes in DNA in dermal cells [13] leading to photoaging. Sagging (ptosis) is normal aging, caused by the effect of gravity on collagen fibers in the skin, but deep wrinkles and pigmentation are not [14]. Darker pigmentation partially protects skin, but sun exposure can wrinkle even darker skin.

Another example of a toxic exposure causing abnormal aging is the effect of air pollution on the lung. Lung function normally decreases with age, but exposure to air pollution worsens lung function [15]. This effect is most marked in smokers [16].

Obesity is not caused by normal aging, but results from excessive caloric intake, often combined with lack of exercise. Even in older adults, exercise prevents muscle atrophy [17].

WHY DOES PREVENTING OTOAGING MATTER?

Why does preventing otoaging matter? If a condition common in old age is indeed part of normal physiological aging, e.g., thinning gray hair, nothing can be done to prevent it. Only cosmetic treatments are available. If a condition is the result of exposures, poor quality diet, or lack of exercise, however, behavior changes may delay the onset or prevent the development

of the condition entirely. Reducing lifetime noise exposure starting early in life will prevent otoaging.

The impacts of otoaging are underestimated for several reasons. Otoaging's economic impact is limited because it becomes prevalent only in the seventh decade of life, when most people are retired. Hearing is invisible. Unlike older persons with visual or mobility impairments, those with otoaging are able to walk, drive, and generally go about their daily lives without apparent difficulty. Otoaging's onset is usually gradual, allowing people to engage in a variety of compensatory strategies for it. Finally, it is commonly believed that unlike cancer, nobody dies from hearing loss. Of course, this isn't true. Hearing loss is the largest single modifiable cause of dementia, a fatal disease [18]. Hearing loss is also associated, most likely causally, with falls, accidents, social isolation, and increased mortality [19].

Even in the modern era, prevention of disease is better than treatment and almost always less expensive for the individual and for society [20]. This is true for otoaging. Amplification with hearing aids is the most common treatment, with cochlear implantation reserved for the profoundly hearing-impaired. Hearing aids are costly; in most countries only a minority of people who might benefit from them can afford their purchase. Perhaps most importantly, hearing aids do not restore normal hearing [21]. Unlike lenses, which provide a visual correction, hearing aids do not provide an auditory correction. For hearing loss, hearing aids provide much less benefit than desired in noisy environments, e.g. restaurants or parties, where being able to converse matters [4, 22].

There is a stigma attached to hearing loss [23], and to wearing hearing aids. For those who have acquired hearing aids, there is significant non-usage. In Wales, where digital hearing aids are provided by the United Kingdom's National Health Service, 18% of people who have acquired hearing aids don't use them at all, and 30% wear them only part of the time [24]. The visible stigma of wearing hearing aids, and the fact that they don't restore normal hearing, are probably the main reasons for hearing aid non-usage. No one likes wearing eyeglasses or using contact lenses, but in industrialized countries almost everyone who needs them acquires and uses them because unlike hearing aids, lenses work well.

Even in countries where the cost of hearing aids is largely covered by the national health system, many people don't want them. As Sternasty and Dhar noted, "In Germany, survey respondents with hearing loss cited the following top 5 reasons for not seeking hearing aids: (1) physical comfort, (2) the inability of hearing aids to restore natural hearing, (3) hearing well enough in most situations, (4) hearing loss not severe enough, and (5) having more serious priorities." [25]

SIX DIFFERENT AREAS OF RESEARCH SUPPORT THE CONCLUSION THAT HEARING LOSS WITH AGE IS NOT PART OF NORMAL PHYSIOLOGICAL AGING

1. Studies of auditory sensitivity done in the 1960s in isolated populations not exposed to noise found hearing preserved into old age. These studies can all be criticized for the testing protocols, equipment used, uncertainty about the actual ages of the subjects, and unknown history of ear or other infections, but they offer the only insights available about what happens to human hearing without excessive noise exposure.

The best known paper may be that by Rosen et al., who studied the Mabaan population in the south Sudan [26]. The Mabaans lived in conditions approximating the late Stone Age with very low ambient noise levels. Older Mabaans had almost as good hearing as younger ones. Dickson et al. studied the Bantu and the Kalahari Bushmen [27]. Their study showed little hearing loss with age in both groups. Jarvis and van Heerden [28] and van der Sandt, Glorig, and Dickson [29] also studied hearing in the Bushmen. Jarvis and van Heerden concluded, "The most striking finding was the absence of presbycusis even in old age." Figure 1, reproduced from Kryter [30], shows the difference in auditory sensitivity between industrialized

populations and the Mabaans. A 10-20 dB decrement in hearing at age 70 may be due to normal physiological aging; greater hearing loss is not.

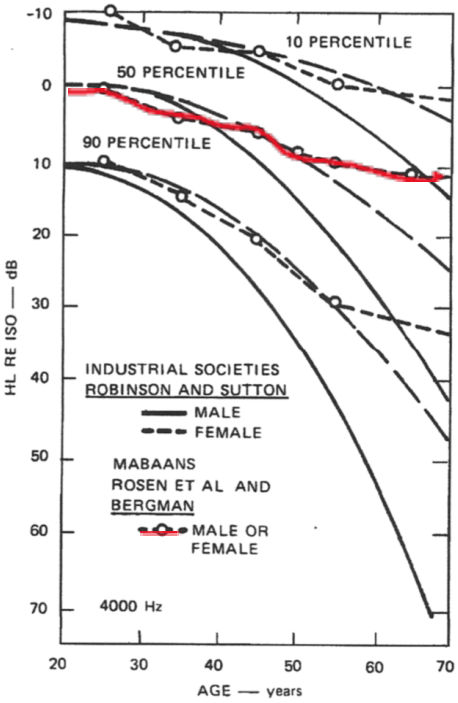

FIG. 11. HLs for young people from the studies of Mabaans and industrialized societies, and the differences in HLs for the older age groups. Test frequency, 4000 Hz. The raw data points for the Mabaans are plotted 10 dB higher (*re*: 15–25-year-olds) than reported on assumption of audiometer calibration error (see text).

Figure 1: Hearing loss in Mabaan and industrialized populations at different age groups. Red highlight added. Reproduced with permission from Kryter KD. Presbycusis, sociocusis and nosocusis. *J. Acoust. Soc. Am.* 1 June 1983; 73 (6): 1897–1917. https://doi.org/10.1121/1.389580; Figure 11. Copyright 1983, Acoustical Society of America.[30]

2. Occupational noise exposure causes hearing loss, with exposure to greater amounts of noise for longer periods of time causing more hearing loss. This research is the basis for occupational noise exposure limits in the United States [31] and European Union.

3. At birth, male and female infants have similar hearing, but in industrialized societies auditory sensitivity in males declines beginning in the second decade of life. This gender disparity continues throughout life [30, 32]. The cause is thought to be greater noise exposure in boys and men, initially from recreational activities and later from occupational exposures. It is rare for women to work in noisy environments, except perhaps in textile mills. Flamme et al. used dosimetry to document that men in Kalamazoo County, Michigan had greater noise exposure than women in everyday life [33]. Estrogen has a protective effect on hearing [34], but as studies of hearing loss in female textile mill workers show, estrogen does not prevent NIHL [35].

4. If hearing loss was part of normal physiological aging, one would expect to find similar rates of hearing loss in all populations, just as many if not most older individuals everywhere in the world have thinning gray hair. When epidemiologic studies show varying prevalence of a condition in different populations, there must be some environmental, genetic, or other factors or influences causing the difference.

5. If hearing loss was part of normal aging, one might expect it to be distributed across all frequencies bilaterally. Instead, hearing loss occurs in the frequencies to which the ear is exposed, with occupational studies showing asymmetric hearing loss, greater in the ear closest to the noise source [36]. For example, dentists often have unilateral high-frequency hearing loss in the ear nearest the high-speed turbine powering the drill [37].

The only evidence-based safe noise exposure level to prevent NIHL is a time-weighted average of 70 dB for 24 hours, and may be as low as 55 A-weighted decibels for a single noise event and a daily average of only 55-60 dB [38]. The external ear canal tunes broadband frequencies to 4,000 Hertz, leading to hearing loss around this frequency [39]. This is manifested by the audiometric notch on audiograms, the hallmark of NIHL [40]. The presence of the notch in those without occupational noise exposure [41] strongly suggests that everyday noise exposure is causing ARHL [42]. As McBride states, “the notch broadens with increasing exposure, and may eventually become indistinguishable from the changes of aging (presbycusis) where the hearing shows a gradual deterioration at the high frequencies.” [40]

6. Basic science research shows that noise exposure causes biochemical, genetic, and structural changes in cells and subcellular structures in the auditory system, leading to organelle damage, hair cell death, and loss of cochlear synapses [43, 44]. Animal studies confirm human studies based only on audiograms, showing that noise exposure at specific frequencies damages the cochlear hair cells that receive these frequencies [45].

WHAT FACTORS MIGHT CAUSE ARHL?

Those favoring still using the term ARHL cite noise, nutritional, vascular, ototoxic, and genetic causes. Lin states, “The term “age-related hearing loss” is intended to describe the resulting phenotype that results from the cumulative effects of all these factors that exert themselves over the lifetime (i.e., are related to age). I agree that addressing or modifying these factors can help reduce declines in hearing over time.” [46] Noise exposure is the most easily modifiable of these factors.

Dietary intakes vary widely, but it is unlikely that any specific vitamin or trace element deficiencies cause ARHL. Atherosclerosis is widespread, but the impact of vascular disease on hearing loss appears to be minimal. Garcia Morales et al. found that in almost 3,600 subjects averaging 59.4 years of age, a 0.1 mm greater carotid artery intimal medial thickness, considered an indicator of significant atherosclerosis, was associated with a 0.59 dB higher pure tone average hearing threshold level [47]. This is a trivial, clinically insignificant increase in hearing loss. Wattamwar et al [48] reported that in elderly patients (mean age 89 years), those with vascular disease had a low-frequency pure tone average hearing loss of 42.4 dB vs 36.9 dB in those without vascular disease. What caused the 36.9 dB hearing loss in those without vascular disease?

What about ototoxic drugs or genes? Although use of potentially ototoxic drugs is widespread and older patients who take them are at increased risk of progression of hearing loss [49], the prevalence of hearing loss from ototoxic drugs has not yet been determined [50]. Many genes are associated with hearing loss [51], but genome-wide association studies have not yielded estimates of the prevalence of genetically caused hearing loss in a general population [52]. The most likely cause of ARHL, and certainly the most easily modified, is excessive noise exposure.

Many researchers have attempted to establish correlations between animal and human studies of ARHL. A recent paper, however, suggests that there are important differences between animal ears and human ears, with the animal studies not being directly relevant to human ARHL. Wu et al. stated,

> "Our analysis of over 120 autopsy specimens shows that inner-ear sensory cell loss can largely explain the audiometric patterns in aging, with minimal contributions from the stria vascularis, the "battery" that powers the inner ear, previously viewed as the major locus of age-related hearing dysfunction…. Our data also show that hair cell degeneration in aging humans is dramatically worse than that in aging animals, suggesting that the high-frequency hearing losses that define human presbycusis reflects avoidable contributions of chronic ear abuse to which aging animals are not exposed." [53]

Additional evidence that hearing loss is not part of normal aging comes from a longitudinal study of hearing in a defined population in Charleston, South Carolina [54]. The analysis in the paper was done to use patterns of hearing loss associated with cochlear pathology in animal models to define schematic boundaries of human audiograms, something later shown by Wu et al. not to be appropriate because of differences between human and animal cochlear anatomy and physiology [53]. Despite this, the paper still provides important information, with a small group of subjects having normal hearing according to the WHO classification [1]. Details of the subject ages in each category are not available, but the mean age was 69.9 years with 94.4% of subjects >60. The Older-Normal hearing threshold levels in the upper left audiogram in Figure 2 are remarkably similar to those found by Rosen et al. in the Mabaans shown in Figure 1.This would appear to confirm the hypothesis that a decrease in hearing of 10-20 dB at age 70 may be normal, and that as shown in the other audiograms in Figure 2, hearing loss >20 dB hearing threshold level is the result of pathological aging likely caused by cumulative excessive lifetime noise exposure.

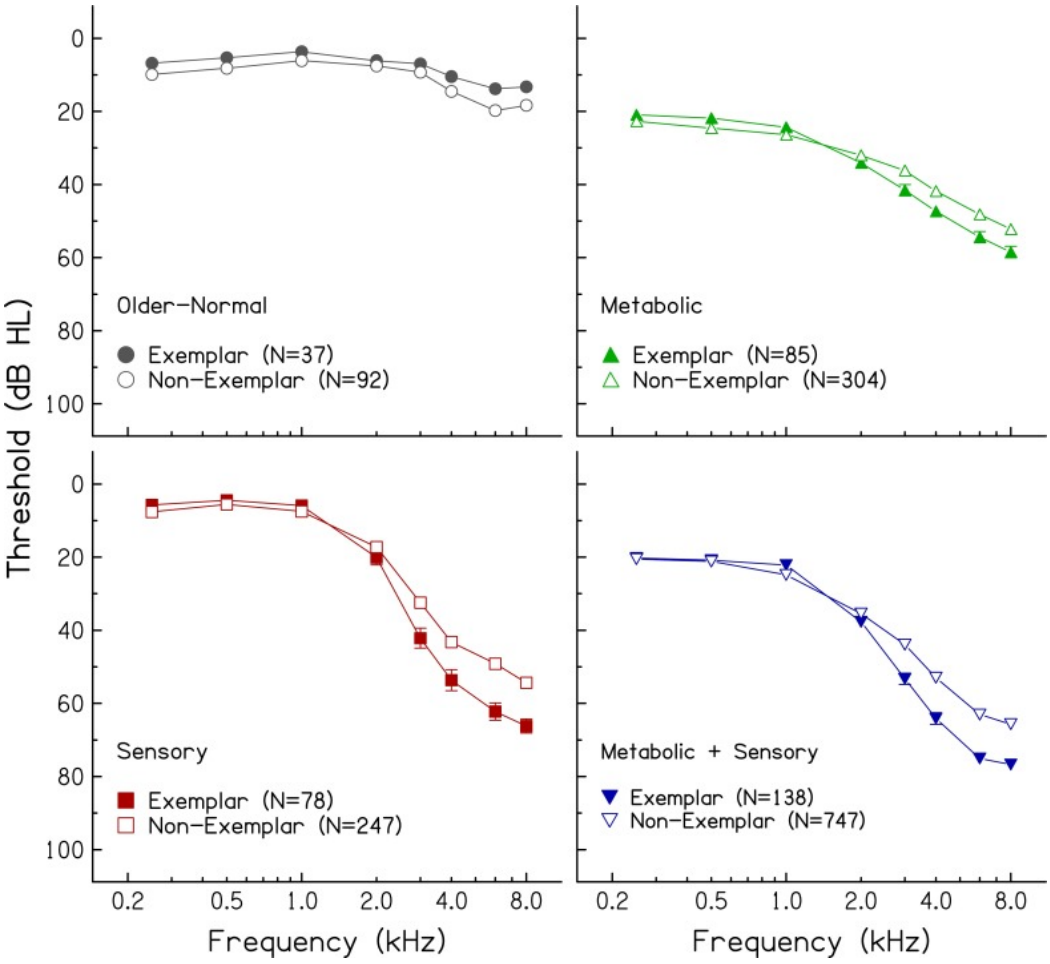

Figure 2: Mean audiograms and standard errors of exemplars (filled symbols) and non-exemplars (open symbols) in four audiometric phenotypes. Reproduced with permission from Dubno JR, Eckert MA, Lee FS, Matthews LJ, Schmiedt RA. Classifying human audiometric phenotypes of age-related

hearing loss from animal models. J Assoc Res Otolaryngol. 2013 Oct;14(5):687-701. https://pmc.ncbi.nlm.nih.gov/articles/PMC3767874/ [54]

CONCLUSION

The combination of observational and epidemiologic studies showing a clear dose-response relationship between noise exposure and hearing loss, with basic science studies explaining how noise damages auditory cells, strongly suggests that hearing loss with age is not caused by normal physiological aging but is rather the cumulative effect of excessive lifetime noise exposure on the ear. Otoaging must be added to the list of "diseases of civilization" caused by modern lifestyles in industrialized countries [55].

The proof of this hypothesis would require well-done longitudinal studies measuring noise exposure, ideally continuously, correlated with measurements of auditory sensitivity, conducted over decades from birth until death. Such studies are unlikely ever to be done due to complexity, the impracticality and cost of measuring all sound exposures, and decades-long follow-up of the subjects.

Based on the existing evidence, it appears that hearing loss with age is largely the result of noise exposure, i.e., otoaging is really NIHL in elderly persons. Terminology matters; words influence how people think. Livingstone-Banks stated that, "how we define diseases has an impact on how (and how effectively) we research and treat them" [56]. The words, "and how we prevent them" should be added. To accurately reflect causality, what is now called ARHL should be renamed *sociocusis* [30] or *noise induced hearing loss in elderly persons* (NIHLEP) [57]. If the effect of sunlight (UV light) on the skin is called *photoaging* [14], perhaps an even better word to describe both the premature aging of cochlear hair cells and synapses caused by noise and the end result, hearing loss in old age, is *otoaging*. The terms *presbycusis* and *age-related hearing loss* should be relegated to the proverbial dustbin of history.

Based on the research of Dillard et al.[58], WHO seems to understand that noise exposure is the major cause of hearing loss, estimating that 1.1 billion young people are at risk of developing NIHL from recreational noise exposure [59]. Not from nutritional causes, not from genetic causes, not from metabolic factors, not from ototoxic drugs, but from excessive noise exposure. Undoubtedly, these young people will have what is now called ARHL, almost entirely preventable, when they reach old age.

No more research is needed to know that noise exposure causes hearing loss, that hearing loss in old age is not part of normal physiological aging, and that reducing noise exposure starting early in life will preserve hearing well into old age. It's time to convince the public to decrease its noise exposure, and time for elected officials and regulators to take steps to reduce noise exposures because of their auditory and non-auditory health effects. A quieter world will be a better and healthier world for all.

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These thoughts were first presented at the 12th Congress of the International Commission on Biological Effects of Noise in Zurich in June, 2017 [10]. They were published in a non-peer-reviewed journal in 2022 [60]. Brief versions of the updated analysis were published in letters appearing in the New England Journal of Medicine in 2024 [61] and in JAMA Otolaryngology-Head and Neck Surgery in 2025 [57]. A poster with the updated analysis was presented at the Acoustical Society of America in Honolulu, Hawaii on December 4, 2025, with a manuscript

submitted to Proceedings of Meetings on Acoustics. The sole purpose of the current presentation and conference paper is to share my ideas with, and to get feedback from, an international audience. The conference paper is © Daniel Fink MD, 2026.

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Noise as a Public Health Problem

Assessing the hearing of classical music students

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ABSTRACT

The paper provides an update on the first pilot reported at ICBEN 2023. Since the introduction of the UK's Control of Noise at Work Regulations research has been undertaken in collaboration with a leading conservatoire investigating the hearing acuity of more than 6000 students between 2007 and 2025. A standard audiometric screening method was employed for both entry and exit testing of undergraduate and postgraduate students. Since 2021 1427 musicians have had their audiometric screening-based test supplemented with otoacoustic emission based (OAE) hearing assessment, n=1290, using Hearing Coach firmware/software, In the last year of testing a 98% success rate was achieved. Results showed that screening audiometry did not follow the standard population as given in ISO 7029 with 95% of students having normal hearing, 4% with mild loss and 1% with significant loss, compared to the typical 75, 20, 5% distribution. However, the OAE results had a 77, 17, and 6% split based on outer hair-cell damage percentage less than age and twice the age of the student criteria. The OAE test methodology was found to be quicker, and more convenient. This provides reassurance that otoacoustic emissions are an excellent tool for assessing hearing health.

INTRODUCTION

The Control of Noise at Work Regulations 2005 (CoNAWR2005) [1] were introduced in the UK to protect employees from health risks associated with noise. With regards to sound exposure, it is known that excessive exposure results in Noise Induced Hearing Loss (NIHL) typically at 4 kHz [2]. Approximately half of NIHL occurs within the first 3 years of excessive sound exposure with the remaining NIHL occurring over the following 42 years [3,4]. Therefore, it is critically important to protect new employees at the earliest opportunity as such Otoacoustic Emissions may provide an answer [5].

Since 2007, through a long-term collaboration with the Royal Academy of Music (RAM), approximately 330 students each year have been assessed using automated audiometric based screening based on pure tone audiometric (PTA) to determine hearing acuity [6]. This study found that most classical music students had negative hearing thresholds, whereas ISO 1999 [3] prescribed that half of 18-24 year olds. The number of students with none or negative hearing thresholds has increased over the past 18 years, see figure 1. This demonstrated that pure tone audiometry may not be the ideal test procedure for classical musicians.

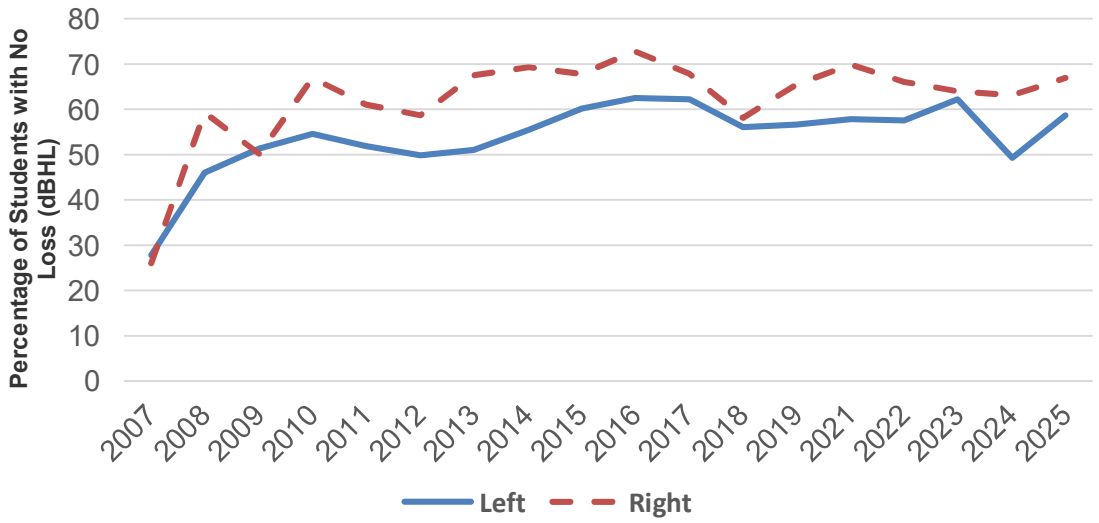

Figure 1. Annual percentage of the student population with no hearing threshold shift, n=6000

OTOACOUSTIC EMISSIONS

OAE based hearing assessments have been used to test the hearing acuity of new-born babies. It has been shown that a reduced OAE amplitude is a precursor to NIHL and hence may act as a biomarker for susceptibility to NIHL [7]. Results of a pilot study were presented, n=502, at ICBEN 2023 [5]. This new work extends the investigation to clearly demonstrate the ability of DPOAEs to highlight the earliest signs of hearing damage and to determine a rule of thumb criteria to categorize that damage in a simple and understandable way that account for the subject's age.

THE RESEARCH STUDY

In July 2021 a study of 1427 classical music students was undertaken over a five-year period. The annual hearing conservation programme commenced with a one-hour virtual seminar on risks to hearing associated with the sound of music performance. The hearing assessments were undertaken in the Acoustics Laboratory of London South Bank University. The assessment consisted of a short questionnaire, completed as a one-to-one interview, that included information on instrument studied and years of music exposure plus additional information on leisure activities, part-time work, and music listening habits. Each student was allocated a 15-minute slot for the appointment, which comprises of DPOAE (1000 to 6500 Hz) using a Path Medical Senti system [8] using Hearing coach software/firmware [9] and automated screening PTA (500-8000 Hz) using two calibrated Amplivox CA850 Mark IV audiometers installed in soundproof booths compliant with ISO 8253 [10]. The results were explained in terms of Outer Hair Cell (OHC) Damage percentage to the student using the proposed rule of thumb, "damage less than the patient's age indicates normal hearing acuity" which was proven in [5] and the hypothesized "damage twice the patient's age indicates poor hearing acuity". Currently Hearing Coach only defines absolute OHC damage, see Table 1.

Table 1: Hearing Coach Category Criteria based on Outer Hair Cell Damage (%)

Hearing Coach	Hearing Category	Estimated OHC Damage
Normal Hearing	Good	<21%
Mild Hearing Loss	Warning	21<41%
Moderate Hearing Loss	Warning	41<61%
Severe Hearing Loss	Referral	61<81%
Profound Hearing Loss	Referral	>=81%

STUDY RESULTS

Otoacoustics emission assessments totalled n=1290 taken over a 5 year period. This compares to the 1427 screening audiograms taken, a 90% success rate; the success rate did improve in the final year to 98%. The average age of the students was 22.05 years with 12.5 years of practice and/or playing. Figure 2 shows the population ranked by OHC damage (%) with lines added for the average and twice the average age of the classical music students.

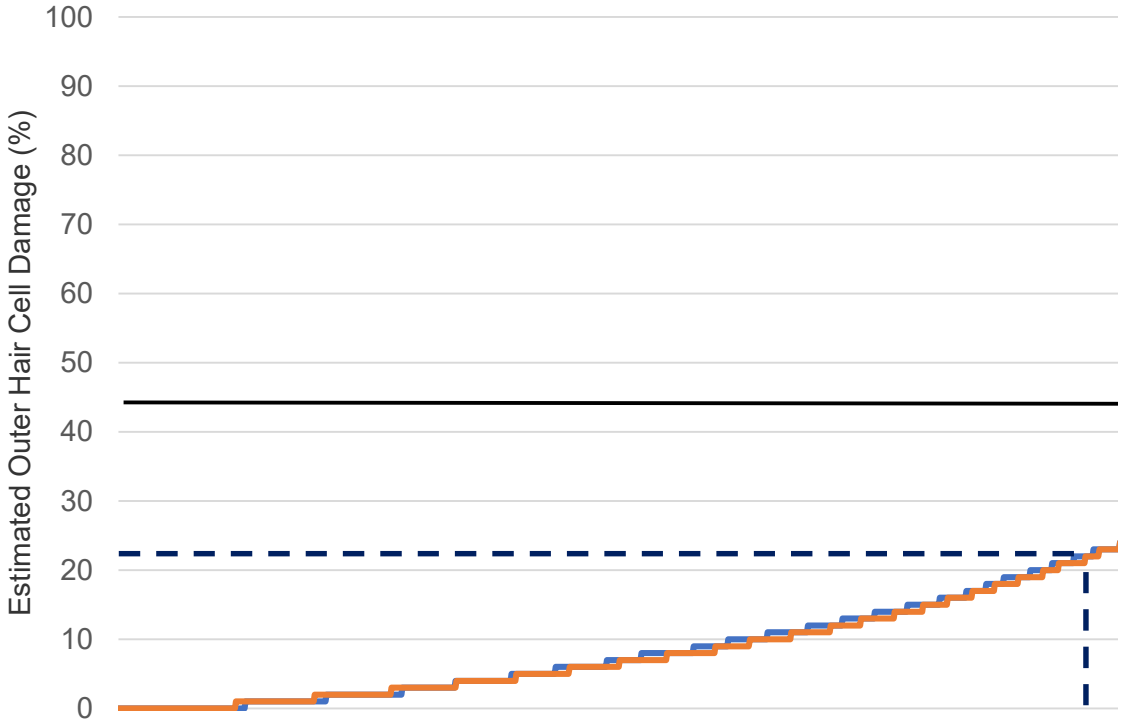

Figure 2. Ranked subjects' outer hair cell damage (%) with average (---) and twice age lines (—), n=1290

From figure 2 it can be clearly seen that each ear has a very similar level of OHC damage. Secondly, no damage was seen until the 125th Musician, thus approximately 10% of the student population had no OHC damage. For the hypothesis set out in the ICBEN 2023 paper, n=503, that OHC damage should be less than the age of the music student to be considered "Normal" hearing. In this extended study further evidence shows the 993rd ranked musician, giving approximately 75% of the population having OHC damage less than or equal to their age. For the proposed hypothesis that "Poor" hearing should have the criteria of OHC damage twice the age of the musician gave the 1213th musician, approximately the 94th percentile.

If the Hearing Coach criteria is used, as shown in Table 1, Then the classical music student population categories have the results as shown in Table 2.

Table 2: Music student population percentage based on Outer Hair Cell Damage (%)

	Using Hearing Coach Categories		**Using Hypothesis Categories based on Subject Age**	
	Left Ear	Right Ear	Left Ear	Right Ear
No Damage	10.0	9.2	10.0	9.2
Normal Hearing	73.5	74.1	76.7	77.2
Mild Hearing Loss	24.0	23.7	17.3	16.4
Severe Hearing Loss	2.5	2.2	6.0	6.4

This analysis presented in Table 2 shows similar distributions for both ears in terms of student population categorization. However, comparing the distribution of the two categorization schemes, the Hearing Coach criteria does not discriminate as much as the hypothesized criteria. The hypothesis can be proven, the distribution closely matching the ISO 7029 standard [4] 75, 20 and 5 percentile population categorizations, +/- 3%. In addition, the new approach accounts for the subject's age, a traditional consideration in hearing assessment.

Coming to the screening audiometry results, summed hearing thresholds (dBHL) from 1 to 6kHz per ear, n=1427. Figure 3 shows the ranked results for the student population with the additional of the 50 dBHL mild loss and 95 dBHL significant loss lines(male).

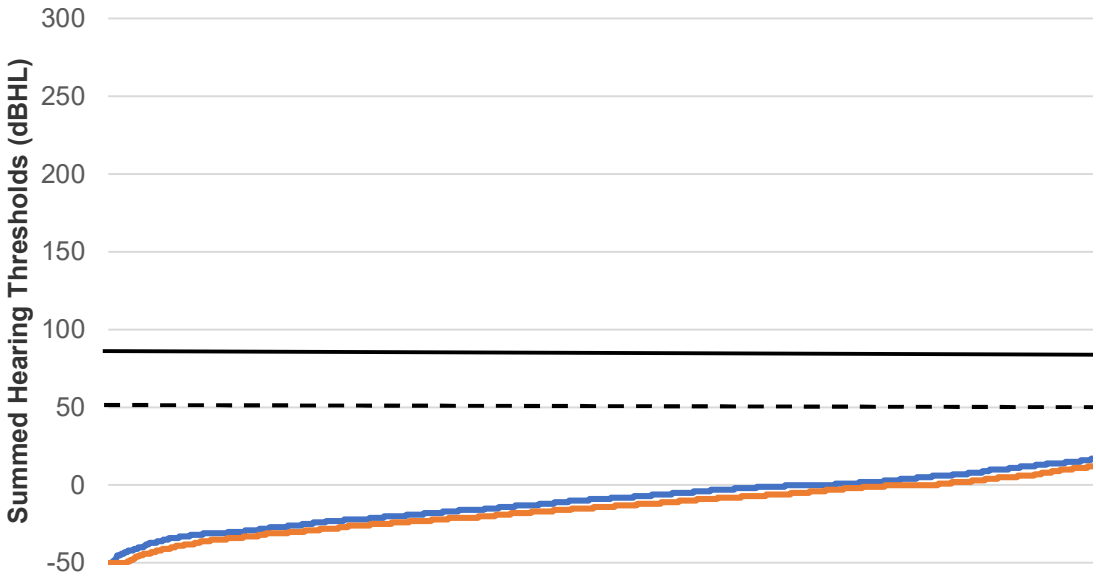

Figure 3. Shows ranked summed hearing thresholds (dBHL) with guidance lines for mild (---) and significant (—) hearing thresholds shifts (18-24 year old), n=1427

It can be seen from Figure 3 that 5 students outscored the instrumentation, -10 dBHL at each frequency (1000 to 6000 Hz) and 22 students for the right ear, 0.3% and 1.5% of the population, respectively. The zero summed hearing threshold shifts point should be found for the 723rd student but was found for the 852th and 973rd musician for the left and right ears, respectively, the 60th and 68th percentile of the population. This confirms that for audiometry the right ear has better hearing acuity than the left ear [11]. This is something not found in the DPOAE results, indicating the hypothesis that the neural connection involved in the processing of sound is responsible for the difference, not the ear itself.

From the UK HSE guidance [12] "Mild" levels of hearing loss, a summed 50 dBHL hearing threshold shift, with 45 dBHL for females, assuming an 18–24-year-old population. This occurred for the 1394th and 1419th student approximately at the 98th percentile. "Significant" level of hearing loss, summed hearing threshold shifts of greater than 95 dBHL, 76 dBHL for females. This occurred at the 99th percentile of the student population for either ear.

Table 3 summarizes the analysis for the 18-24 years old group in terms of audiometry hearing health categories [12] and hypnotized OAE categories.

Table 3 Percentage of the student population in three hearing health categories

	Population Percentage ISO 1999		**Study Percentage Audiometry n=1427**		**Study Percentage DPOAE n=1290**	
Hearing Category	Left Ear	Right Ear	Left Ear	Right Ear	Left Ear	Right Ear
Normal	75.0	75.0	94.8	96.4	76.7	77.2
Mild	20.0	20.0	4.2	2.8	17.3	16.4
Significant	5.0	5.0	1.0	0.8	6.0	6.4

Table 3 shows the student musician population does not follow that given in ISO 7029 [3] where 75% of people are expected to have “Normal” hearing acuity, there was approximately 95% of the classical musicians with “Normal” hearing acuity. This result was reinforced by the approximate 4% of the population with “Mild” levels of hearing loss compared to 20% for the general population. Finally, 1% of the students fell into the “Significant” hearing loss category compared to 5% found in the general population. Hence, the objective DPOAE based hearing assessment approach for the study population can be clearly seen to be significantly more matched to the general population than the screening audiometry results.

This was further examined by taking the 10th, 50th and 90th percentiles for the summed hearing thresholds and the OHC damage (%), as seen in Table 4.

Table 4. Study population 10th, 50th,90th percentiles-based hearing threshold shifts and outer hair cell damage (%).

Population Percentile	**Summed Hearing Thresholds (1, 2, 3, 4, 6 kHz dBHL)**		**OHC Damage (%)**	
	Left Ear	Right Ear	Left Ear	Right Ear
10th	-31	-35	0	1
50th	-6	-12	10	10
90th	17	12	36	35

By investigating the statistical distribution of the hearing health results it can be clearly seen from Table 4 that the left ear audiometry results are all worse than the right ear for each percentile. It should be noted that the left ear was the first ear tested after familiarization had taken place. This compares to the DPOAE results which were very similar for the left and right ear in terms of OHC damage (%). Both the 10th and 50th percentiles gave negative summed hearing thresholds for both left and right ears. For the OHC damage (%) the 10th percentile was nearly zero damage with the 50th percentile giving a balanced 10% hearing damage. At the 90th percentile the summed dBHL for both ears would fall into the Normal hearing category. This compares to approximately 36% OHC damage for the 90th percentile meaning close to double the age, the hypothesized point where early signs of damage had occurred.

CONCLUSIONS AND FURTHER WORK

A new hearing assessment method has been tested for a specific group, that of students studying at a leading music conservatoire. This paper has shown that otoacoustic emissions are an excellent supplementary tool for hearing health surveillance. The DPOAEs clearly showed greater discernment for early signs of hearing damage than audiometry. These results confirmed the results of initial pilot and feasibility studies [5].

The study hypothesized that the hearing categories given by Hearing Coach [9] could be improved by also considering the subject’s age. It has been found that using relative criteria rather than absolute outer hair cell damage (%) does increase the discernment of the scheme. The relative criteria categorizing normal hearing with subject age less than the damage (%), significant levels being greater than twice the subject age. This approach provided a population distribution that closely aligned with that provided by the standard ISO 7029 [3] within +/3 %, whereas the Hearing Coach approach was within +/- 4% of the standard distribution.

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Beyond fit-testing: toward real-time in-ear dosimetry for hearing protection

As part of ICBEN Symposium "Standardization and future developments in hearing protection and fit testing"

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ABSTRACT

Over the last 25 years, hearing protection device (HPD) fit-testing has become an essential component of effective hearing conservation programs. First explored in the mid-1970s, HPD fit-testing (HPFT) was initially developed to quantify, for a specific individual, the actual attenuation achieved by a hearing protector. In 2000, the authors introduced an objective dual-microphone method - Field Microphone in Real Ear (F-MIRE) - designed for a new generation of instant-molded custom earplugs. Since then, the method has been adapted and successfully integrated into commercial systems for fit-testing non-custom earplugs and earmuffs.

However, despite its widespread success, HPFT remains inherently limited: it provides only a static snapshot of attenuation for a given HPD at a single point in time. It cannot capture how fit degrades during real-world use, nor can it account for the true spectral and temporal characteristics of the noise that actually reaches the eardrum.

To overcome these limitations, the last decade has seen significant advances in in-ear dosimetry, a continuous monitoring approach using a microphone placed inside the occluded ear canal, beneath the HPD. This paper highlights the most recent developments shaping this emerging paradigm, including the ANSI S1.46 draft standard for industrial and military applications and the ITU-T SL-AD proposal developed with the World Health Organization (WHO) "*Make Listening Safe initiative*" for consumer devices. Together, these efforts point toward the next major evolution in hearing conservation: replacing traditional HPFT with real-time, individualized, in-ear exposure monitoring.

INTRODUCTION

The history of hearing protection is, in many ways, a history of successive approximations. For decades, hearing conservation programs have attempted to infer the sound pressure level reaching the human cochlea from measurements performed in the workplace, on a manikin, on the body of a worker, or from laboratory attenuation values printed on a box of earplugs. Each of these steps has been useful, and none should be dismissed. Yet each step is also a reminder that the quantity of

interest is not the sound level in a room, nor the sound level on a shoulder, nor even the nominal attenuation of a hearing protector. The quantity of interest is the sound exposure of a given individual, at the entrance of the auditory system, over the real duration of use.

Hearing protection device fit-testing (HPFT) was a decisive improvement because it brought the assessment closer to the individual wearer. Instead of relying only on group attenuation values, HPFT gives access to an individual attenuation estimate, commonly expressed through a personal attenuation rating (PAR). This concept has proven extremely powerful for training, for identifying improper insertion, for verifying that a given HPD is suitable for a given worker, and for documenting that hearing conservation programs are not merely distributing protectors, but also checking that these protectors can be used effectively [1-4].

This paper argues that HPFT should now be regarded as a necessary but insufficient step. The next step is to measure, or at least estimate with a quantified uncertainty, the sound pressure level at the eardrum itself. This is the purpose of in-ear dosimetry. The shift is not cosmetic. It changes the measurement target, the instrumentation, the uncertainty budget, and the language used to communicate risk. It also creates a bridge between occupational hearing conservation, military noise exposure, and consumer safe-listening systems, which until now have largely evolved in parallel.

LIMITS OF HEARING PROTECTOR FIT-TESTING

The first and most obvious limit of HPFT is that it remains a snapshot. A fit test is usually performed at the beginning of a shift, during a training session, during annual audiometric follow-up, or when a new protector is introduced. It tells us what attenuation was achieved at that moment, with that protector, under that instruction, and with that insertion on a given worker. It does not tell us whether the same protector will be worn correctly two hours later, after the wearer speaks, sweats, moves, removes one plug to communicate, reinserts it in a hurry, or replaces a disposable foam plug after lunch.

The second limit is that HPFT estimates attenuation rather than exposure. This distinction is fundamental. A worker may have an excellent PAR but a moderate ambient exposure, or a modest PAR but a very high exposure spectrum dominated by frequencies where the protector performs poorly. Conversely, a communication headset, an electronic hearing protector, or a tactical earplug may attenuate external sound while also delivering speech, alarms, radio communication, warning sounds, or active sound restoration underneath the protector. A fit test cannot quantify that electroacoustic contribution.

The third limit is spectral and temporal. Most HPFT systems reduce a complex attenuation function to a single-number rating. This is operationally convenient, but it masks the fact that noise-induced damage risk is driven by energy integrated over time, filtered by frequency weighting, and shaped by the actual spectrum of the exposure. A single PAR cannot determine whether the residual protected exposure is excessive unless it is combined with the actual noise exposure spectrum. In practice, this combination is often approximate.

The fourth limit is physiological. A conventional personal noise dosimeter mounted on the shoulder is affected by placement, body diffraction, orientation, and the acoustic field. When HPDs are worn, the body-worn dosimeter remains outside the protection and therefore measures a quantity that is intentionally decoupled from the ear canal sound pressure. The protected exposure must then be inferred by subtracting an attenuation value, often with large uncertainty. At that point, one could argue that the hearing conservation program is no longer measuring protected exposure, but reconstructing it from imperfect proxies.

Finally, HPFT does not address wearer-induced disturbances (WIDs) : the wearer's own voice, chewing, coughing, footsteps, hand-arm vibration, cable-borne noise, and other body-conducted sounds may become particularly salient in an occluded ear canal because of the occlusion effect. Several studies have shown that the wearer's own voice can influence dosimetry measurements [5, 6]. Whether all such contributions should be treated as damaging sound exposure remains an open question, but they are part of the acoustic reality underneath the protector and must therefore be measured, classified, or at least reported.

able 1: From HPD fit-testing to in-ear dosimetry

Approach	Primary output	Main advantage	Main limitation
Laboratory HPD attenuation testing	Group attenuation statistics and labeling values	Standardized and reproducible under controlled conditions	Does not represent the ”real world” attenuation
HPD fit-testing	Individual attenuation estimate or PAR	Excellent tool for training and individual verification	Static snapshot; does not measure actual protected exposure
Body-worn noise dosimetry plus attenuation estimate	Estimated protected exposure	Operationally simple and compatible with existing regulations	Depends on subtraction of uncertain HPD attenuation values
In-ear dosimetry	Measured or estimated eardrum exposure	Continuous, individualized, and compatible with passive and active devices	Requires calibration, correction, WID handling, and uncertainty management

WHY IN-EAR DOSIMETRY IS A NECESSARY NEXT STEP

In-ear dosimetry moves the measurement point from the environment of the wearer to the ear canal of the wearer. In its simplest form, it relies on a miniature microphone located somewhere along the ear canal or at the ear canal entrance, typically underneath an earplug, earmuff, communication earpiece, hearable, or headset. The measured sound pressure is then corrected to estimate the corresponding sound pressure at the eardrum. In this sense, the in-ear dosimeter does not merely ask whether the HPD is well fitted. It asks what sound pressure level actually remains at the target location during real use [7-12].

The practical advantages are significant. In-ear dosimetry can capture fit degradation over time, the effect of reinsertion, the contribution of intermittent high-level events, and the residual exposure created by imperfect attenuation in a real noise field. It can also account for the actual spectrum of the residual exposure. This matters because two users with the same ambient level and the same PAR may receive different eardrum-level exposures because of different ear canal morphologies, different insertion depths, different protector leakage paths, or different device acoustics.

In-ear dosimetry also enables the measurement of exposure generated inside the device. This is increasingly important because modern HPDs are no longer only passive barriers. They may include communication receivers, active noise reduction, ambient sound restoration, level-dependent transmission, Bluetooth audio, or radiocommunication channels. From an exposure point of view, all of these sources are acoustically real. They contribute to the sound pressure at the eardrum even if they are not present in the ambient field. This is why the evolution from HPFT to in-ear dosimetry is also an evolution from attenuation assessment to complete protected-exposure assessment.

A further advantage is that in-ear dosimetry can support real-time feedback. HPFT is mostly pedagogical: it teaches a user how to fit the protector correctly. Real-time in-ear dosimetry can become behavioral: it can warn the user, the supervisor, or the device itself when protected exposure is trending toward an excessive cumulative value. For industrial and military environments, this creates a direct pathway toward exposure management. For consumer devices, it creates a pathway toward safe-listening interfaces that are less dependent on nominal headphone sensitivity and more representative of the user's actual acoustic exposure.

TECHNICAL CHALLENGES OF TYMPANIC EXPOSURE MONITORING

The attractiveness of in-ear dosimetry should not hide its technical difficulty. Measuring at or near the eardrum is a metrological problem, not simply an embedded-electronics problem. The in-ear microphone is almost never located exactly at the tympanic membrane. It is placed where the device geometry allows it to be placed, often several millimeters away from the eardrum, and this distance is acoustically important. Above approximately 2 kHz, small changes in location inside the ear canal can

create large changes in measured sound pressure because of standing waves, ear canal resonance, insertion depth, and individual morphology [11].

The first challenge is therefore the microphone-to-eardrum correction (MEC). A microphone located in the occluded ear canal measures local pressure, not automatically eardrum pressure. The correction may be generic, based on insertion-depth tables, or individualized, based on microphone-in-real-ear and real-ear attenuation at threshold measurements. Generic corrections are attractive because they are simple, but they bring a substantial uncertainty. Individualized corrections are more precise, but they require additional procedures and are therefore more demanding to deploy.

The second challenge is that the correction depends on the source path. Sound entering passively through the HPD material and leakage paths does not necessarily create the same microphone-to-eardrum relationship as sound generated by an internal receiver (a.k.a. miniaturized loudspeaker). A loudspeaker placed in the ear canal can generate local near-field or evanescent components at the microphone port that do not propagate in the same way to the eardrum. Therefore, the electroacoustic path must often be handled separately from the passive acoustic path. This is particularly important for communication headsets, hearables, and active systems.

The third challenge is calibration. The in-ear microphone and its acquisition chain require factory calibration, field functional checks, and a proper treatment of sensitivity drift. Miniature microphones may be affected by the warm and humid conditions of the ear canal. Probe tubes, when used, can introduce frequency-dependent effects and should not be checked blindly at 1 kHz. The calibration problem is thus inseparable from the mechanical and acoustical design of the device.

The fourth challenge is WID handling. The conservative approach is to include everything measured by the in-ear microphone in the cumulative exposure. This has the advantage of safety and simplicity, but it may overestimate exposure if self-generated sounds are partly treated differently by the auditory system. A more advanced approach, the sole one documented and validated to date, is to use an external microphone and an in-ear microphone to monitor coherence and identify when the in-ear signal is dominated by a wearer-generated sound rather than by external noise [12]. Other WID-detection strategies can be developed, but they must be validated, documented, and reported transparently.

The fifth challenge is the proper communication around the so-called “uncertainty statement!. A measured value without an uncertainty statement can easily give a false sense of precision. Conversely, a large uncertainty is not a reason to avoid measurement; it is a reason to report a conservative estimate. In the proposed approach, uncertainty components are combined following the general logic of the *Guide to the expression of uncertainty in measurement* (GUM), and the reported exposure includes a safety margin. In practical terms, high uncertainty leads to a larger conservative overestimation, while better instrumentation and calibration reduce the margin and bring the estimate closer to the true value [13, 17].

There are also limits that must be stated explicitly. In-ear dosimetry measures air-conducted pressure in the ear canal. When double or triple protection produces attenuation values approaching bone-conduction limits, the residual cochlear stimulation may no longer be adequately represented by the air-conducted pressure measured under the protector. Similarly, impulsive noise can be analyzed, but fractional-octave corrections applied to impulsive waveforms require particular care. These are not reasons to abandon in-ear dosimetry; they are reasons to standardize it properly.

ANSI S1.46 AND ITU/WHO STANDARDIZATION

ANSI S1.46: industrial and military in-ear noise exposure assessment

The ANSI S1.46 draft standard was initiated, under the hospice of the *American National Standard Institute S1 WG7*, to address exactly this gap: the absence of a dedicated metrological framework for tympanic noise level monitoring devices and dosimeters [14]. Its scope is deliberately broader than conventional HPFT. It applies to devices worn in or around the ear, including circum-aural, supra-aural, and intra-aural devices, and it considers both passive transmission through the device and active electroacoustic transmission through embedded receivers [13].

The technical architecture of the draft can be summarized through several functional blocks. First, the microphone signal is converted into calibrated acoustic pressure using a daily calibration gain and factory calibration factors. Second, the signal is analyzed in fractional-octave bands, compatible with established acoustical filtering practice. Third, microphone-to-eardrum -MEC- corrections are applied to estimate tympanic pressure. Fourth, when a receiver is present, the receiver contribution is treated through a separate electroacoustic pathway so that the passive and active contributions can be combined energetically. Fifth, uncertainty components are added by frequency band to obtain a conservative exposure estimate.

A central concept in the draft is that the reported outcome should be an eardrum-referenced exposure metric, not merely a legacy free-field equivalent level. The proposed terminology, Sound Level At EarDrum (SLAED), reflects this paradigm shift. It is an overall A-weighted equivalent sound level at the eardrum, normalized to the relevant exposure duration. The name is intentionally distinct from conventional body-worn dosimetry metrics because the measurement includes ear canal acoustics, HPD effects, active receiver contributions when applicable, WID treatment, and individual or device-specific transfer functions.

The draft also recognizes that different levels of precision must coexist. A simple device may rely on generic insertion-depth corrections and therefore carry a larger uncertainty budget. A research-grade or high-precision system may use individualized corrections, acoustical test fixture measurements, human-subject procedures, and validated WID detection. The important point is that these approaches are not presented as equivalent. They are organized through their intrinsic measurement uncertainty. This creates a pragmatic standardization path: innovation is not blocked, but the consequence of uncertainty is made visible in the reported exposure.

This is also why the draft does not define what is excessive. It defines how to measure, calculate, correct, combine, and report. Damage-risk criteria remain the responsibility of the relevant regulation, military doctrine, occupational exposure limit, or future eardrum-based health criterion. In other words, ANSI S1.46 is primarily a metrological standard. It prepares the ground for better exposure assessment, but it does not replace the policy decision that defines an acceptable or unacceptable exposure.

ITU-T SL-AD: consumer safe-listening transducers

In parallel, the joint effort between the Internation Telecommunication Union (ITU) and the World Health Organisation (WHO) “Make Listening Safe” initiative has been evolving from a model based mostly on electrical signal monitoring and headphone sensitivity toward a more accurate dosimetry framework for close-fitting listening devices. The ITU-T H.870 guidelines already recognized that dose estimation for personal listening devices is affected by many uncertainty components, including headphone sensitivity, production tolerances, fit, artificial-ear characterization, real-ear variability, and exposure from other sources [15]. The ITU-T currently has a work program (H.SL-AD) focused on integrating safe-listening metrics into devices to protect hearing (building upon ITU-T H.870). The proposed ITU-T SL-AD work builds directly on this observation and extends it toward an architecture that can incorporate in-ear microphones and eardrum-referenced exposure data [16].

The proposed device classification is important. Category 1 devices rely on the headphone returning exposure information to a media player or companion display. Category 1.5 devices perform this function autonomously and display the cumulative dose themselves. Both categories can be receiver-based, when the digital signal delivered to the receiver is used for dose estimation, or microphone-based, when an in-ear microphone measures the acoustic field in the ear canal. Category 2 devices rely on the digital signal sent to the receiver and require headphone sensitivity information to be provided to the media player. Category 3 devices cover legacy analog systems, for which the receiver’s electrical sensitivity must be entered manually or retrieved from a registry.

This classification may appear simple, but it has major implications. For receiver-based systems, the signal used for dose calculation must be taken at the right point in the audio chain. In particular, active noise control signals should not be counted as exposure if they are control signals intended to reduce residual sound pressure at the eardrum. For microphone-based systems, the measurement approach converges with the ANSI S1.46 logic: fractional-octave exposure data, uncertainty

components, tympanic-level interpretation, and, where possible, separation of the different contributors to in-ear sound pressure.

The ITU/WHO proposal also creates a practical implementation path by specifying the type of information that may need to be exchanged between a transducer and a media device. For Category 2 devices, this includes headphone frequency response or sensitivity data, potentially exchanged through wired or wireless metadata. For Category 1 and 1.5 devices, this includes cumulative exposure data in fractional-octave bands and shorter reporting intervals, such as 30-second equivalent levels. The conceptual link with ANSI S1.46 is clear: a consumer safe-listening ecosystem can benefit from the same uncertainty-aware metrology being developed for industrial and military exposure assessment.

FROM STANDARDIZATION TO IMPLEMENTATION

The convergence between ANSI S1.46 standard and ITU-T SL-AD recommendation is particularly timely because hearing protection and listening devices are no longer separate technological worlds. The same physical form factor may be sold as a hearing protector, a tactical communication device, a hearable, an earbud, a hearing aid accessory, or a consumer headset. The user, however, has only one auditory system. From a public-health perspective, it is therefore increasingly difficult to justify a fragmented metrological framework in which occupational noise, military communication, and consumer listening are estimated by incompatible methods.

The transition will not happen at once. HPFT will remain important because it is simple, pedagogically powerful, and already accepted in many hearing conservation programs. In-ear dosimetry should not be positioned as a rejection of HPFT. Rather, it should be positioned as its natural extension. HPFT verifies that a protector can provide sufficient attenuation under test conditions. In-ear dosimetry verifies what exposure is actually received during use. The two methods answer different questions, and the second question becomes increasingly important as protectors become connected, active, and multifunctional.

Implementation will require manufacturers to treat acoustical metadata as part of the device, not as an afterthought. Receiver sensitivity, frequency response, calibration state, uncertainty components, and cumulative exposure data will need to become machine-readable. This is where the proposed recommendations intersect with communication protocols. The recommendations described here are being passed to the *Bluetooth Special Interest Group* (Bluetooth SIG), and they shall influence future standards by encouraging wired and wireless audio ecosystems to carry the information needed for accurate, uncertainty-aware, safe-listening dosimetry.

This point is critical. If a media player or operating system displays a dose estimate without knowing the actual transducer sensitivity, without knowing whether the signal is pre- or post-processing, without accounting for fit and ear canal variability, and without receiving uncertainty data, the displayed value may look precise while remaining fundamentally uncertain. Standardized handshaking between the audio source, the transducer, and, where applicable, a companion display is therefore not a convenience feature. It is a prerequisite for trustworthy dose communication.

CONCLUSION

HPD fit-testing has changed hearing conservation by making attenuation individual. Its value remains unquestionable. Yet fit-testing alone cannot determine the sound exposure that actually reaches the eardrum during real use. The future of hearing protection, communication headsets, hearables, and safe-listening devices will require continuous, individualized, eardrum-referenced exposure monitoring.

In-ear dosimetry provides this path, but it must be standardized carefully. The measurement requires microphone calibration, microphone-to-eardrum correction, separate treatment of passive and active sound paths, management of wearer-induced disturbances, and a rigorous uncertainty budget. ANSI S1.46 addresses in its current draft document these elements for industrial and military exposure assessment. ITU-T SL-AD, developed within the WHO “Make Listening Safe” initiative, extends the same logic toward consumer close-fitting listening devices. Together, these initiatives define a

common technical language for the next generation of hearing conservation and safe-listening standards.

The essential message is simple: the field is moving beyond asking whether the protector fits. It is beginning to ask what the ear actually receives. That question is more difficult, but it is also the right one.

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Supporting workers with hearing loss in high noise environments

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ABSTRACT

An estimated 9 million adults of working age in the UK have hearing loss and the proportion in employment is growing as we work for longer.

High noise environments present particular challenges for workers with hearing loss. Directive 2003/10/EC requires that risk assessments consider ‘any effects concerning the health and safety of workers belonging to particularly sensitive risk groups’ and ‘any indirect effects on workers’ health and safety resulting from interactions between noise and warning signals or other sounds that need to be observed in order to reduce the risk of accidents’.

Twelve workers with acquired hearing loss contributed to a facilitated discussion and an evaluation of hearing protection in order to produce recommendations to inform risk assessment and hearing protector selection. Of these, eight were hearing aid users, one used a bone-conduction hearing device, one used a cochlear implant and a hearing aid, and two were on a waiting list for hearing aids.

Their lived experiences highlighted a disconnect between occupational health and audiology, low awareness of schemes for obtaining practical support, limited consideration of the specific risks to health and safety encountered by workers with hearing loss, and a lack of guidance in how to select and use hearing protection without introducing safety risks.

The hearing protector evaluation demonstrated the feasibility of sourcing hearing aid-compatible solutions and highlighted the importance of having the opportunity to try different hearing protectors under realistic conditions to find a comfortable, practical solution that preserves awareness of sounds and the ability to communicate.

INTRODUCTION

One in three adults in the UK are deaf, have hearing loss or tinnitus [1]. Of those adults who are of working age, an estimated 9 million have hearing loss in one or both ears [2] and the proportion in employment is growing as the average retirement age increases. Yet the needs of people with hearing loss and tinnitus in the workplace often go unmet. A UK survey on the experiences of 1072 workers with hearing loss revealed that over half (54%) had worked at some time without disclosing their hearing loss for fear of losing their job, for fear of being treated unfairly or because they 'thought that reasonable adjustments wouldn't be able to be made and therefore there was no point telling people at work' [3].

High noise work environments present particular challenges for workers with hearing loss. It is known that work-related accident risk increases with decreasing hearing ability, particularly in high noise environments. Girard et al. observed that 'for each dB of hearing loss, a significant increase of the risk of injury occurs' [4]. Picard et al. reported that the accident category most strongly associated with hearing loss was 'passive accidents' defined as 'the victim becoming the involuntary recipient of some mechanical energy' due to for example, 'not hearing warning signals in occupational noise, or being confounded by its masking effect' [5].

Directive 2003/10/EC requires that risk assessments consider 'any effects concerning the health and safety of workers belonging to particularly sensitive risk groups' and 'any indirect effects on workers' health and safety resulting from interactions between noise and warning signals or other sounds that need to be observed in order to reduce the risk of accidents' [6]. UK Health and Safety Executive (HSE) guidance document L108 advises, 'In general, hearing aid users working in noisy environments should continue to use their hearing aids to maintain hearing ability and minimise safety risks. Where personal noise exposure is at or exceeds an upper exposure action value, or the individual is working within hearing protection zones, hearing aid users should be supplied with and make full and proper use of personal hearing protection' [7]. However, there is little guidance available for employers on how to assess the specific risks to health and safety created by exposure to workplace noise when workers have hearing loss and tinnitus, and in particular, how to select and use hearing protection without increasing the safety risks. Furthermore, very few hearing aids (HAs) are available that are also certified as hearing protection.

A test and certification procedure has been established by the Institute for Occupational Safety in Germany for combined HA and hearing protection systems for use in high noise workplace environments. Test Principle GS-IFA-P165 [8] enables manufacturers to demonstrate that a hearing protection earmold (for use with a HA) conforms to hearing protector requirements standard BS EN 352-2:2020 [9] in support of the EU Type Examination Certification required for category III Personal Protective Equipment. This test and certification procedure applies to behind-the-ear (BTE) and receiver-in-canal (RIC) type HAs, and the hearing protection earmold is by necessity, unvented. Vented or open fitted HAs are often used for individuals with good residual low frequency hearing, to prevent moisture build up within the ear canal, or to reduce the occlusion effect. At present it is not intended that a user would switch between closed and open fitting earmolds, limiting the option of a combined HA and hearing protector to individuals where a closed fitting is acceptable.

German Statutory Accident Insurance Test Principle DGUV 312-002 [10] is required to be used by hearing care professionals when dispensing HAs in combination with hearing protection earmolds. It specifies the requirements and test methods to ensure that workplace sound levels presented by the HA are safe using a version of hearing protector requirements standard BS EN 352-7:2020 [11], and that speech and warning signals in the workplace remain audible. At a criterion level of 110 dBA, the combination of the attenuated noise and the sound reproduced by the HA is limited to a diffuse-field corrected level of 85 dBA; a level

that may be too low for workers with ‘severe’ hearing loss [12]. There is currently no equivalent procedure for setting up combined HA and hearing protection systems in the UK.

A passive hearing protector in addition to hearing loss can make it exceptionally difficult to hear, as the attenuation provided by passive protectors tends to be greater at the higher frequencies where the effects of hearing loss are typically worse. This combination of high frequency hearing loss and passive protector attenuation can make warning signals and speech communication inaudible or difficult to localise [13] putting workers with hearing loss at a disadvantage and at greater risk compared to their colleagues with normal hearing.

Hearing protector guidance standard BS EN 458:2025 [14] suggests the use of hearing protection with a flat-frequency response to mitigate the effects of excessive attenuation at higher frequencies; however, most protectors with a flat-frequency response provide lower noise attenuation overall and may not be suitable for high noise work environments. Sound-restoration level-dependent hearing protectors are a potential solution as these reproduce sounds in the environment at a safe level under the protector, allowing the user to benefit from a high level of protection whilst maintaining awareness of alarms, warnings, workplace transport, and the ability to communicate.

This paper presents the findings from a facilitated discussion and an evaluation of eight sound-restoration level-dependent hearing protectors by a focus group of twelve workers with acquired hearing loss to produce recommendations to inform risk assessment and hearing protector selection.

METHODOLOGY

The facilitated discussion was conducted in four groups of three workers and included prompts for discussion in the themes: hearing background, hearing device use, risk assessment, and hearing protection use (Table 1). A rapid functional assessment and subjective evaluation of eight sound-restoration level-dependent earmuffs and one passive earmuff was undertaken to explore potential issues with hearing device compatibility and feedback, and to identify human factor issues relating to fit and usability. A pragmatic, low tech approach was adopted for this assessment that could be adapted for use in any workplace to provide sufficient information to support the selection of hearing protection by workers with hearing loss. The questionnaires were developed using Level 1 of the Human Factors Assessment Framework [16,17,18] (Table 2).

Table 1: Facilitator prompts for discussion

Categories	Example questions
Hearing background	“How long have you had hearing loss?” “What type and severity of loss do you have?”
Hearing device use	“What options were you given when your hearing aid was set up?” “What hearing aid programmes and settings do you use at work?”
Risk assessment	“What risks do you encounter that are different for people with normal hearing?” “What are the barriers to mitigating these risks?”
Hearing protection use	“What hearing protection have you been using?” “What guidance have you been given on using hearing protection?”

Table 2: Functional assessment and subjective evaluation questionnaire format

Format	Categories	Example questions	Tasks/Questions
Functional assessment (9 tasks, task success scored yes/partially/no)	Fit and feedback	"Were you able to put the hearing protector over your hearing aid(s) without causing feedback?"	T1: HA feedback T2: Physical fit over HA
	Donning, doffing, adjustment and seal	"Were you able to achieve and maintain a good hearing protection seal (e.g. when turning your head)?"	T3: Donning/doffing in reasonable time T4: Able to adjust to size T5: Able to achieve and maintain seal
	Communication in quiet and noisy backgrounds	"Were you able to communicate effectively in a noisy background?"	T6: Comms in quiet with HA T7: Comms in quiet without T8: Comms in noise with HA T9: Comms in noise without
Subjective evaluation (3 questions, scored using 7-point Likert scale, e.g. very uncomfortable to very comfortable)	Wear comfort	"How uncomfortable or comfortable was the hearing protector with your hearing aid(s)?"	Q1: Comfortable with HA Q2: Comfortable without
	Acceptability	"How acceptable or unacceptable would this hearing protection be for your role?"	Q3: Acceptable for role

Eight models of sound-restoration level-dependent earmuff were sourced from four manufacturers (earmuffs A-H in Table 3). The earmuffs were either of the headband type or helmet-mounted. An earmuff providing passive protection only was included for comparison (earmuff I). Measurements of earcup depth, the inner cushion dimensions, cushion seal width and outer cushion dimensions are illustrated in Figure 1 and listed in Table 3. Helmet-mounted earmuffs were supplied with compatible helmets as per BS EN 352-3:2020 [15]. Headband earmuff E was slim enough to be worn under a helmet and was evaluated in combination with a helmet.

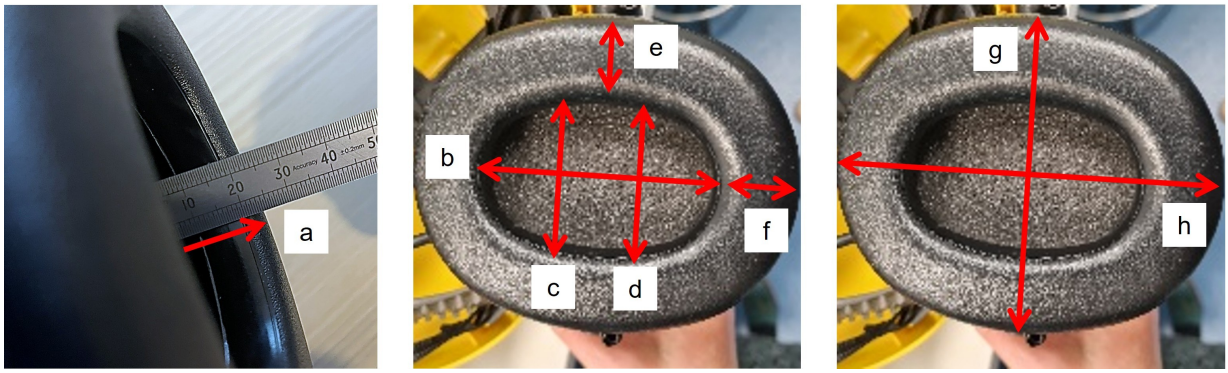

Figure 1: Measurements of earcup depth (a), the inner cushion dimensions (b, c, d), cushion seal width (e, f) and outer cushion dimensions (g, h)

Table 3: Earmuff dimensions

Earmuff †helmet-mounted ‡passive	**Inner ear cushion dimensions (mm)**				**Seal maximum width (mm)**		**Outer cushion dimensions (mm)**	
	depth (a)	height (b)	upper width (c)	lower width (d)	side (e)	bottom/ top (f)	width (g)	height (h)
A	17	66	40	40	15	20	75	100
B †	20	63	37	37	20	20	80	105
C	20	63	37	37	20	20	80	105
D †	20	64	38	38	20	20	80	105
E	20	64	37	37	20	20	80	105
F	10-15	67	40	40	15	16	73	100
G	18	68	40	40	15	16	71	100
H	17-20	65	35	35	22	22	80	100
I †‡	35-40	66	41	38	20	20	77	102

RESULTS

Facilitated Discussion

The focus group comprised twelve workers with acquired hearing loss, with severity of loss ranging from mild to profound. Eight workers used BTE or RIC type HAs, one used a non-surgical bone-conduction hearing device (BCHD), one used a cochlear implant (CI) and a BTE type HA, and two workers were on a waiting list for HAs.

Feedback from those workers with hearing devices indicated they had received limited support for hearing device use in the workplace and a lack of opportunity for adjustment:

- *"the audiologist instructed me to take my hearing aid out when using hearing protection"*
- *"… no guidance for use at work"*
- *"little explanation of functionality..."*
- *"[My HA] has 3 programmes – I can't tell much difference"*
- *"Many [settings] were turned off as he didn't think I needed them – the audiologist went through the settings so I could make an informed decision about which settings to use but you don't have option to change your mind."*

Awareness of options for practical support in the workplace was low. One worker commented, *"when people aren't sure and don't know what help is available, they either don't start the process or don't continue".* The importance of *"hearing needs assessments"* that are *"repeated regularly"* was echoed by other workers in the group discussions, highlighting the need for proactive workplace needs and risk assessment processes.

Hazards identified in the discussion groups where there was a perceived increase in risk due to reduced hearing ability included:

- Unfamiliarity with new sites
- Not receiving safety briefings due to difficulty *"deciphering speech in a noisy environment",* communicating *"with people you don't know"* and having to *"guess what is being said based on context"*
- Workplace transport, e.g. *"vehicles moving and lack of directional hearing"*
- Fire, e.g. *"not hearing the fire alarm and instructions"*

Controls proposed by the workers to minimise these safety risks included:

- Using level-dependent sound restoration hearing protection
- Using assistive devices or work phones as dedicated wireless microphones to transmit speech via Bluetooth to HAs worn under hearing protection
- Using speech-to-text to aid communication
- Lip reading and/or communication skills training (for individuals with hearing loss)
- Deaf/hearing loss awareness training (for colleagues of individuals with hearing loss)
- Structuring activities *"to avoid having to communicate in high noise areas"*
- Using alerting devices for alarms
- Agreeing an alternative means of communication using visual or hand signals

Three out of the twelve workers contributing to the discussion groups had received ad hoc specialist advice and were using sound-restoration level-dependent earmuffs. The remainder reported having received limited or no guidance on how to select hearing protection that took into account their hearing loss, and were using passive earmuffs, roll-down earplugs, or banded-earplugs, requiring removal of their hearing devices. Workers commented that the *"problem with [passive] hearing protection is the inability to communicate".*

Functional Assessment

The functional assessment comprised nine tasks in three categories. Task success was scored +2 (yes), +1 (partially) and 0 (no). Average scores for each earmuff are in Table 4.

The ten workers who wore hearing devices assessed the feasibility of fitting the earmuffs without causing feedback. Feedback often occurs when a HA is brought into close proximity with a reflective surface, such as the earcup of an earmuff and is more likely to occur for earcups of a shallow design containing acoustically nonabsorptive materials. Notably earmuff F with the shallowest earcup depth was reported as being the most likely of the earmuff selection to cause HA feedback (task T1).

All workers with BTE or RIC type HAs answered 'yes' for at least three or more pairs of earmuffs in terms of achieving a good fit over their HAs without causing feedback. Where there were issues with fit or feedback, they occurred for the following reasons:

- Earmuff cushions *"interfering with the controls"* and *"changing the settings"* on HAs
- Difficulty fitting BTE HAs under earmuffs without breaking the seal
- Intermittent HA feedback with head movement or *"dependent on head position"*
- Noise caused by the earmuff cushions *"rubbing on the hearing aid"*
- Stiff push buttons on the earcups that when pressed *"hurt [the] ears"*

Table 4: Average scores for earmuffs A - I, tasks T1 - T9

Earmuff †helmet-mounted ‡passive	**Fit and feedback**		**Donning, doffing, adjustment and seal**			**Communication in quiet and noisy backgrounds**			
	T1	T2	T3	T4	T5	T6	T7	T8	T9
A	1.4	1.6	2.0	1.9	1.8	1.4	1.9	1.0	1.5
B †	1.8	1.9	1.8	1.7	1.5	1.8	1.9	1.2	1.1
C	1.4	1.6	2.0	2.0	1.9	1.8	2.0	1.4	1.4
D †	1.5	1.7	1.6	1.8	1.6	1.4	1.8	0.5	1.0
E	1.6	1.6	1.8	1.8	1.6	1.8	1.8	0.8	1.2
F	1.2	1.6	1.8	1.5	1.6	1.6	2.0	0.6	1.1
G	1.4	1.4	1.5	1.5	1.5	1.6	2.0	0.6	1.3
H	1.6	1.8	1.8	1.8	1.8	1.7	1.9	0.6	0.9
I †‡	1.6	1.7	1.6	1.6	1.6	1.2	0.9	0.4	0.8

It was not possible to fit any of the earmuffs over both the pinna and the non-surgical BCHD. BCHDs are typically positioned behind the ear but unlike BTE or RIC type HAs, the sound processor is not in contact with the pinna and hearing protector earcups are not large enough to enclose it (Figure 2).

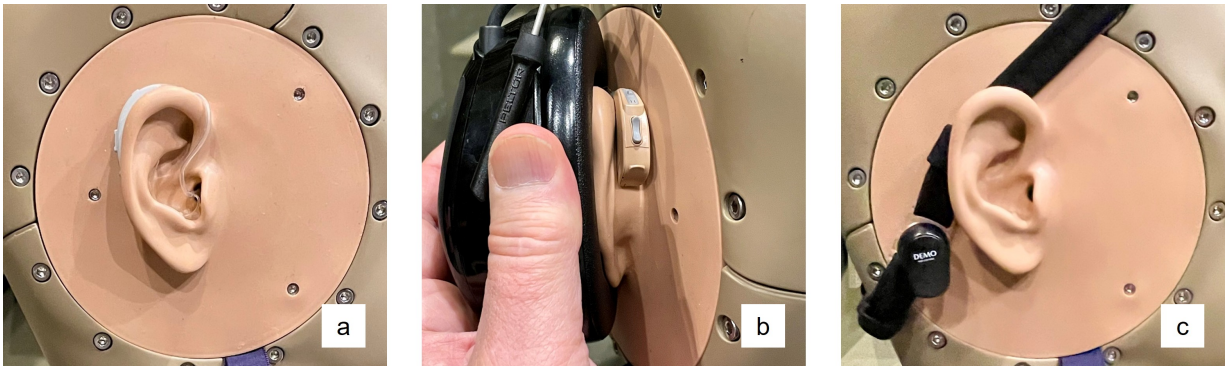

Figure 2: Position of RIC and BTE type HAs (a) and (b), and non-surgical BCHD (c)

All twelve workers rated their ability to don and doff each PPE combination in a reasonable amount of time, to adjust their PPE to the correct size, to achieve and maintain a good earmuff seal. Comments for helmet-mounted earmuff D indicated that issues with donning were due to difficulty pushing the earmuffs inwards into the working position: *"I wasn't happy closing the cups and forming a seal"*, *"I think mechanically they will be damaged in use. The muff doesn't fit well with the helmet"*, *"protectors seemed very stiff to fit"*.

The tasks of donning, doffing and maintaining a good seal for helmet-mounted earmuffs were further hampered by the helmet chin straps: *"Difficult to manage with chin strap"*, *"Helmet strap got caught under the muff"*, *"Helmet chin straps break the seal of the hearing protector when head is turned"*. The lower average scores for adjustment and seal (tasks T4 and T5) for earmuffs F and G were primarily due to their size and seal width: *"Too big, gaps around the sides, no proper seal obtained"*.

The workers rated their ability to communicate effectively in quiet and in noisy backgrounds with each earmuff alone, and again with the earmuff worn over their hearing devices where applicable. All twelve answered 'yes' to being able to communicate effectively in a quiet background for at least five or more of the sound-restoration level-dependent earmuffs. Average communication ratings for the sound-restoration level-dependent earmuffs were slightly lower when they were worn with hearing devices (tasks T6 and T8) due to issues with fit and earcup seal, e.g., being *"unable to completely cover hearing aids with ear defender"*. Only four workers reported being able to communicate effectively in a quiet background when wearing passive earmuff I and none answered 'yes' to being able to communicate effectively in a noisy background with this earmuff.

Replicating all of the noise environments that the workers might encounter was deemed impractical for this assessment. A generic noise environment was therefore simulated by reproducing pink noise with an A-weighted equivalent continuous sound pressure level of 84.5 dB as measured at the centre of an arrangement of four loudspeakers in a controlled environment. Average ratings for the sound-restoration level-dependent earmuffs were lower for communication in this noise (tasks T8 and T9), but still more favourable than for passive earmuff I. The workers reported that the sound-restoration level-dependent earmuffs made it *"easier to communicate in a noisy environment, but not a lot"* and that for some devices the *"volume control affected speech and noise equally"*. One worker with asymmetric hearing loss commented that it would be useful to have separate volume controls for the left and right earcups. Although the workers reported less success in being able to communicate in the noisy environment, having the ability to communicate whilst wearing the sound-restoration level-dependent earmuffs when moving in or out of hearing protection zones was valued as it saved the hassle of having to repeatedly and carefully fit or remove the earmuffs over HAs: *"they worked fine in less noisy environments and I was able to communicate without taking them off"*.

Subjective Evaluation

Responses for each of the subjective evaluation questions were scored from -3 to +3. Average scores for each earmuff are given in Table 5.

Table 5: Average scores for earmuffs A – I, questions Q1 – Q3

Earmuff †helmet-mounted ‡passive	**Wear comfort**		**Acceptability**
	Q1	Q2	Q3
A	1.5	1.5	-0.2
B †	1.4	1.8	0.4
C	2.1	2.1	0.9
D †	0.9	1.5	-0.1
E	1.4	1.5	1.1
F	1.0	1.5	0.2
G	0.4	1.1	-0.4
H	1.6	1.5	0.5
I †‡	1.5	1.6	-0.6

All workers rated at least one of the sound-restoration level-dependent earmuffs as providing a ‘comfortable’ or ‘very comfortable’ and an ‘acceptable’ or ‘very acceptable’ hearing protection solution.

All of the earmuffs received at least one rating of ‘comfortable’ and ‘acceptable’, but crucially, there was no single solution that was rated comfortable and acceptable by all of the workers, reinforcing the advice in HSE guidance document L108, which states that ‘The hearing protection supplied should take into account user comfort and preference, compatibility with any hearing aid worn and any particular requirements arising from medical advice’[7].

The workers reported that it was *“eye-opening to hear what is available and to see(?) how well the muffs worked with hearing aids”* and *“great to see and try different types of ear defenders”*. The opportunity to try on and compare earmuffs was also anticipated to make *it “easier ordering PPE”*, particularly with regard to ensuring the correct selection of earmuffs with *“thick versus slim”* earcup designs.

CONCLUSIONS

Feedback from the facilitated discussion highlighted a disconnect between occupational health and audiology, with workplace hearing needs going unmet. Awareness of options for practical support in the workplace for workers with hearing loss was low, highlighting the need for proactive workplace needs and risk assessment processes. The workers reported receiving limited or no guidance in how to select and use hearing protection that took into account their hearing loss.

The rapid functional assessment and subjective evaluation of hearing protection demonstrated the feasibility of wearing earmuffs over HAs without causing feedback and highlighted the importance of having the opportunity to try on different makes and models to find a comfortable, practical solution that preserves awareness of sounds and the ability to communicate.

Earmuff–HA compatibility issues included: the physical act of donning or doffing earmuffs, which can dislodge, change the settings of, and damage HAs; poor fit; intermittent HA feedback with head movement; and noise produced by ear cushion contact with HAs. The tasks of donning, doffing and maintaining a good seal for helmet-mounted earmuffs introduced further compatibility issues, emphasizing the need to check and ensure integration with other PPE.

All twelve workers reported success in being able to communicate effectively in a quiet background for at least five or more of the sound-restoration level-dependent earmuffs. Ratings for sound-restoration level-dependent earmuffs were lower for the communication in noise task, but still more favourable than for the passive earmuff. For workers who prefer to wear their hearing devices under sound-restoration level-dependent earmuffs, this communication functionality reduces the burden of having to carefully don or doff earmuffs over hearing devices, particularly when moving between hearing protection zones or when working in intermittent noise environments.

For BCHDs it was not possible to fit any of the earmuffs over both the pinna and the sound processor. It is important that individuals with BCHDs continue to use hearing protection in high noise environments to protect their remaining hearing. This may require the individual to remove the sound processor part of their BCHD. In such cases a sound-restoration level-dependent hearing protector may still present sounds at a sufficient level to aid communication and awareness.

Limitations & Future Work

Hearing protector guidance standard BS EN 458:2025 [14] and HSE guidance document L108 [7] recommend in-situ listening tests to verify the audibility of warning signals and alarms. This was not conducted as part of the assessment due to the many combinations of warning signals, alarms, and noise environments encountered by the workers in this group. However, audio files for testing warning signal audibility in accordance with German Statutory Accident Insurance Test Principle DGUV 312-002 are available online and could be used to inform risk assessment and hearing protector comparison where in-situ listening tests are not practical [19].

There is evidence indicating that workplace noise exposures for some HA users may need to be lower than the action values in Directive 2003/10/EC [20,21,22]. The potential for excessive amplification depends on an individual's HA prescription, HA noise reduction and volume settings, the level of the ambient noise and earmuff volume setting. The maximum audio output level of sound-restoration level-dependent earmuffs is typically limited to 82-85 dBA. Further research is needed to determine if they can be worn safely together with high gain HAs.

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Noise as a Public Health Problem

The present state and future direction of hearing protector standardization in Europe

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ABSTRACT

This article is part of the symposium "Standardization and future developments in hearing protection and fit testing" and will give an introduction to the standards specifying the testing and evaluation of hearing protectors and requirements for placing a product on the European market. European Committee for Standardization (CEN) Technical Committee (TC) 159 is constantly working to ensure that hearing protector standards keep pace with innovation. This is shown using the case of current standardization project on active noise reduction earplugs.

INTRODUCTION

In Europe the primary legislation applicable to placing a hearing protector on the market is the Regulation (EU) 2016/425 on personal protective equipment (PPE) (see [4]). In general, PPE must meet the essential health and safety requirements stated in Regulation (EU) 2016/425. By fulfilling harmonized standards, it can be presumed that the essential health and safety requirements are met. The list of harmonized standards is kept up to date via publication in the Official Journal of the European Union.

CEN/TC 159 is responsible for writing the standards that include the requirements for hearing protectors. Additionally, this committee develops standards that specify the necessary test procedures, where these are not already defined by the International Organization for Standardization (ISO), and guidance on the selection and use of hearing protectors.

TESTING OF HEARING PROTECTORS

Passive hearing protectors

The product specific standards by CEN/TC 159 are structured such that the requirements are separated from the test methods and are defined in parts 1 to 10 of the EN 352 series. The test methods are defined in EN 13819 part 1 to part 3, or in referenced ISO standards.

The most important of course is the sound attenuation according to ISO 4869-1 (see [5]), which can be achieved with the hearing protector. This standard specifies the subjective method for the measurement of sound attenuation using sound field audiometric tests with 16 test subjects. Hearing threshold levels are determined with and without wearing the hearing protector. The difference between these two threshold levels for a test subject and a given test

signal is the hearing protector's sound attenuation. So, the most relevant performance parameter is derived by subjective real ear attenuation at threshold (REAT) testing (see figure 1), and not by an objective measurement of hearing protector insertion loss with an acoustic test fixture (ATF) according to ISO 4869-3 (see [6]). In general, an ATF (see figure 2) is only used for control of the homogeneity of hearing protector products and where it is not possible (or very complex) or unsafe to use test subjects for microphone in real ear (MIRE) measurements.

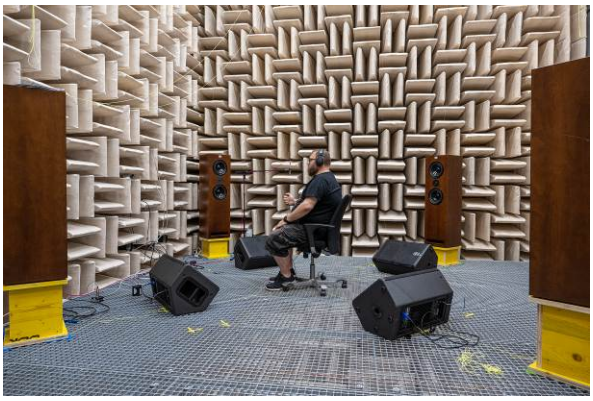


Figure 1: example for the test setup in an anechoic room for REAT testing according to ISO 4869-1

Figure 2: example of an earplug positioned in an ATF for testing of the level-dependent function according to EN 13819-3

In addition to tests of acoustic performance defined in EN 13819-2 (see [2]), mechanical tests such as sizing, headband force, cushion pressure and ignitability must also be conducted and are defined in EN 13819-1 (see [1]). The flow chart in figure 3 illustrates the procedure for testing passive headband earmuffs with a headband made of metal and fluid-filled ear cushions.

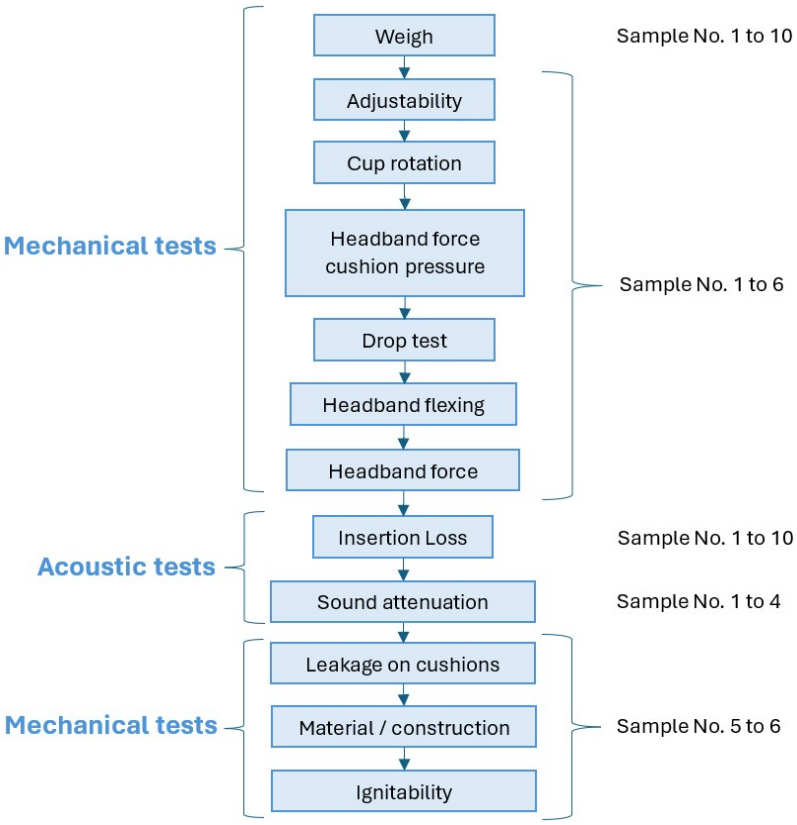


Figure 3: Flow chart of tests on a headband earmuff; following [2]

Hearing protectors with extended functionality

The testing of the performance of passive hearing protectors has been well established for many decades. The testing of additional electronic functionality has also been performed for a long time and is defined in EN 13819-3 (see [3]). The chart in figure 4 gives an overview of the different functions, input possibilities, the corresponding parameters and requirements for hearing protectors with extended functionality.

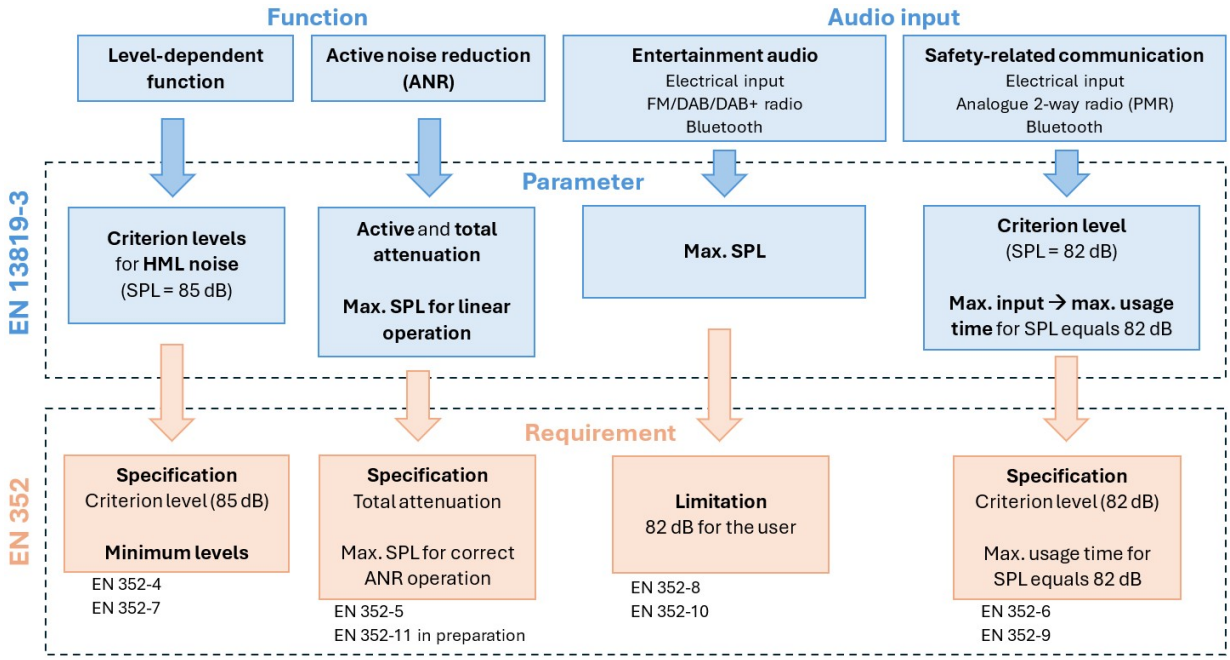


Figure 4: In testing and requirement standards defined supplementary functions and audio inputs on hearing protectors

The market and the functionality of consumer products for entertainment audio and communication ear- and headphones is growing. People want to use products with the same comfort they are already familiar with for their leisure activities for communication and entertainment audio at their place of work. Arbitrary headsets and earbuds are not allowed to be used in high noise workplaces; they are not PPE. The employer is responsible for the health and safety of their employees and can only provide tested and certified hearing protection. Manufacturers are beginning to react to these needs and more hearing protector products are being placed on the market that allow for music streaming and calls.

All these functions, including the two main advanced attenuation functions (level-dependent attenuation and active noise reduction) and relevant transmission paths in figure 4 are now often included in medium-priced consumer products (under 100 Euros). But official checks and certificates for the functions are usually missing in consumer entertainment products. For example, it needs to be verified that any sound restoration (often called ‘hear-through’ or ‘transparency mode’) is working in a safe way and that the device can be safely used in high noise environments up to a certain external sound pressure level (SPL). Or when looking at the inputs for entertainment audio, it must be ensured that listening to music via the device cannot lead to hearing damage.

When a product is to be certified as a hearing protector, it must fulfil the essential health and safety requirements. To facilitate this process, it is necessary that the harmonized standards are always kept up to date and that they adapt to meet the needs of the market, which can be challenging.

EXAMPLE CURRENT STANDARDIZATION PROJECTS

Earplugs with active noise reduction

A test method for active noise reduction (ANR) earmuffs is defined in ISO 4869-6 and was adopted with slight changes in EN 13819-3. However, there are currently no test method or requirements standards for ANR earplugs. CEN/TC 159 is working to address this gap and develop a test method for type-examination and control of homogeneity of production that is easy to perform and reproducible. The decision was made to use an artificial ear instead of the MIRE method according to ISO 11904-1 due to the challenges and safety issues that arise when inserting a microphone into the ear canal behind an earplug. Unlike the measurements for level-dependent earplugs, the insertion loss determined with an ATF cannot be corrected using REAT data. Because of this, and to simulate a non-perfect earplug fit representative of realistic operating conditions for the device, it was decided to introduce a leakage in the ear canal extension that is attached to the ear simulator (see figure 5 and 6). Measurements have been performed with different sized leakages and different methods for introducing the leakage in the measurement setup, exploring the influence on insertion loss. Additionally, the necessary precision of the leakage and usability for the test labs have been considered. In figure 7 the insertion loss of a foam earplug is shown with ear canal extensions that have rectangular leakages of different sizes.

Figure 5: example leaky ear canal extension used to determine the active sound attenuation of ANR earplugs

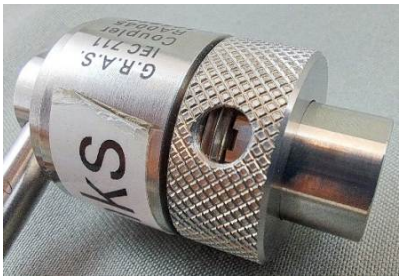


Figure 6: leaky ear canal extension attached to an IEC 60318-4 coupler

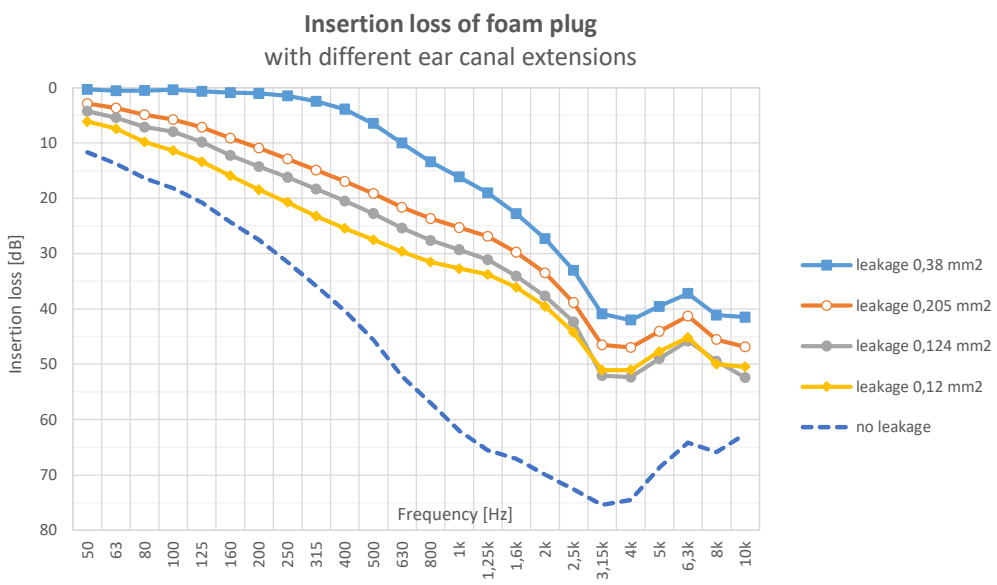


Figure 7: Influence of different leakages on the insertion loss of a foam plug

With this specifically designed setup, the active sound attenuation of the device under test in a diffuse sound field is determined for 8 samples (see figure 8 and 9 for an example setup).

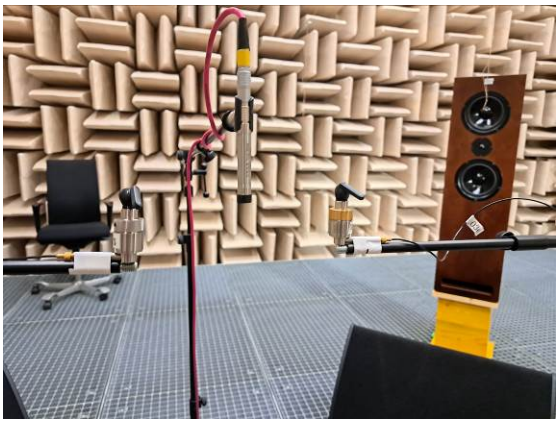
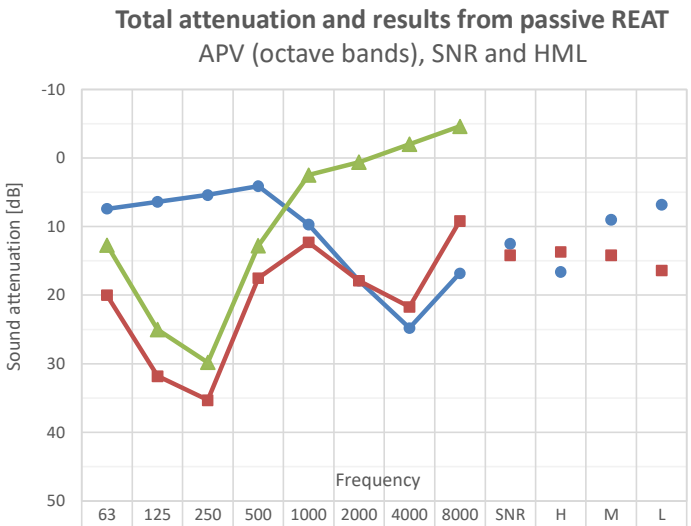


Figure 8: example measurement setup for a pair of earplugs to determine the active attenuation

Figure 9: example earplug positioned in a leaky ear canal extension attached to an IEC 60318-4 coupler

In the next step the mean active sound attenuation is combined with each passive sound attenuation determined with 16 test subjects according to ISO 4869-1 to determine the total sound attenuation. As for passive earplugs, the sound attenuation with ANR turned on is given by mean values and assumed protection values (APV) in octave bands and in form of high-, medium- and low- (HML) frequency attenuation values and as Single Number Rating (SNR) values for easy evaluation of earplug performance by the user.

In figure 10 the typical behaviour of an entertainment audio earbud with ANR is shown. The product delivers a very good active attenuation up to 500 Hz, but at higher frequencies there is slight amplification when ANR is turned on, leading to reduced sound attenuation at higher frequencies. In this case the product cannot be certified as hearing protector, because the sound attenuation in passive mode does not fulfil the minimum requirements of EN 352-2, ensuring that the earplug continues to deliver a basic sound attenuation even when the battery is empty. A better insulating ear tip would be necessary in this case.



	63	125	250	500	1000	2000	4000	8000	SNR	H	M	L
passiv attenuation (REAT)	7,4	6,4	5,4	4,1	9,7	17,9	24,8	16,8	12,5	16,6	9,0	6,8
active attenuation	12,7	25,0	29,8	12,8	2,5	0,6	-2,0	-4,6				
total attanuation	20,0	31,8	35,3	17,5	12,3	17,9	21,7	9,2	14,2	13,7	14,2	16,4

Figure 10: Example sound attenuation of a typical consumer audio earbud with ANR

The active sound attenuation is usually determined with an external broadband noise between 85 dB and 95 dB SPL. To be sure that the ANR system is working the same way over a wide range of SPL the linearity of the device under test must be verified. The user must know what the maximum external SPL is, for which the ANR of the earplug still functions correctly. In addition to the total attenuation, this second parameter is important for the user to make an informed decision before procuring ANR earplugs.

When the test method standard is complete and inter-laboratory comparisons demonstrate good accordance and the practicability of the method, the requirements for ANR earplugs will be defined. The requirements standard will include the minimum performance requirements and also the necessary information to be included in the user manual and on the packaging of the product.

Further current projects of CEN/TC 159

A rising number of products for children and even toddlers are available on the market. This led to the conclusion that a test standard and a standard on the requirements are necessary. Because children cannot be used as test subjects for REAT testing according to ISO 4869-1, another approach for testing and evaluation of such types of products must be developed.

An European standard on the requirements for amplitude-sensitive hearing protection devices for impulsive noise environments will follow the development of a test method to measure the response of hearing protectors with high-level impulsive noise on an acoustic test fixture by ISO (see [7]).

CONCLUSION

Standards are crucial for ensuring the safety, reliability and effectiveness of hearing protection. They detail repeatable methods for performance testing and characterization and provide a means for manufacturers to demonstrate compliance with agreed benchmarks in Europe. Advancements in hearing protector electroacoustic functionality are driving changes to hearing protector standards, requiring the development of new test methods to ensure that essential health and safety requirements are met.

The development of standards on hearing protection presumes that experts with different backgrounds (such as manufacturers, users, authorities' representatives, testing labs, notified bodies for PPE) work together to develop applicable test methods and requirements.

REFERENCES

[1] EN 13819-1:2020+A1:2024, Hearing Protectors - Testing - Part 1: Physical test methods

[2] EN 13819-2:2020, Hearing Protectors - Testing - Part 2: Acoustic test methods

[3] EN 13819-3:2019+A1:2024, Hearing Protectors - Testing - Part 3: Supplementary acoustic test methods

[4] Regulation (EU) 2016/425 on personal protective equipment (PPE), 9th of March 2016

[5] ISO 4869-1:2018, Acoustics - Hearing protectors - Part 1: Subjective method for the measurement of sound attenuation

[6] ISO 4869-3:2007, Acoustics - Hearing protectors - Part 3: Measurement of insertion loss of earmuff type protectors using an acoustic test fixture

[7] ISO/DIS 4869-7:2025, Acoustics - Hearing protectors - Part 7: Method to measure the response of hearing protectors with high-level impulsive noise on an acoustic test fixture

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Raising the PAR: Global regulatory momentum in hearing protector fit testing

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ABSTRACT

Hearing protector fit testing (HPFT), first conceptualized in the 1970s, has emerged as a best practice in occupational hearing loss prevention. Factors such as an increased availability of fit-test methods and systems, heightened attention on the importance of personal protective equipment fit, and the awareness of needing appropriate attenuation, rather than the highest single number attenuation value, have contributed to the adoption of HPFT. Scientific research has revealed multiple benefits of HPFT and new educational textbook chapters, resources, and courses have been created. In parallel, the HPFT regulatory landscape has expanded, extending rapidly around the world. The purpose of this paper is to review the milestones in the development of HPFT. This includes best practices documents, standards, and regulatory requirements. Specific focus is given to existing North American standards that describe the personal attenuation rating (PAR) and set performance criteria for HPFT systems, provide implementation considerations and guidance, and allow the PAR to be used in the selection of hearing protection devices. Future directions of standards and/or standard revisions are considered toward advancing HPFT as an integral component of occupational hearing loss prevention programs.

INTRODUCTION

The evolution of hearing protector fit testing (HPFT), from concept to commercialization, from novelty to normalization, and from best-practice recognition to regulatory requirement, is literally “raising the PAR” in occupational hearing loss prevention. The PAR, in this case, refers to the personal attenuation rating, which is a metric to quantify the amount of attenuation achieved by a given fit of a hearing protector by an individual user. The idea is to take the traditional laboratory-based attenuation testing, used for labeling hearing protection devices (HPDs), into the workplace. This allows employers to discover the attenuation workers achieve when fitting an HPD the way they typically do on the job and offers a unique training opportunity. An HPFT program can help improve HPD selection, fit, and use and potentially drive better hearing loss prevention outcomes.

Many factors have contributed to the elevated status of HPFT: an increased number of fit-test methods and systems, heightened attention on the importance of personal protective equipment fit, and a growing awareness of maintaining situational awareness in noise (striving for “appropriate” attenuation rather than choosing the highest attenuation option). Scientific research has revealed the need for HPFT and revealed multiple benefits of HPFT. New textbook chapters have been published, and educational resources and courses have been developed to help inform employers, safety and health professionals, and workers [1].

As the interest in HPFT has grown, the regulatory landscape has expanded. The purpose of this paper is to review milestones in the development of HPFT, particularly regarding standards and regulatory changes, and to project what might be on the horizon for raising the PAR to new heights.

KEY MILESTONES

HPD attenuation

The attenuation of HPDs has long been assessed in laboratory settings based on the real-ear attenuation at threshold (REAT) method. These measurements are conducted following standardized procedures in tightly controlled environments. A key factor contributing to HPD attenuation is how well the devices are fitted. For laboratory REAT assessments, the HPDs are often fitted by highly trained subjects [2] or even fitted for the test subjects by the experimenter [3]. There has also been an effort to develop standardized REAT methods that use naïve test subjects to fit the HPDs, such as Method B of ASA/ANSI S12.6 [4].

HPDs are labeled with attenuation ratings, such as the noise reduction rating (NRR) or single number rating (SNR), that are derived from the laboratory REAT measurements. However, the attenuation measured in the lab, even with naïve test subjects, tends to exceed the attenuation achieved by workers wearing HPDs in the real world. This led to the development of “derating” recommendations such as was proposed in 1998 by the National Institute for Occupational Safety and Health [5], where the labeled attenuation is reduced to more closely reflect the real-world observed performance. Even then, derating schemes are based on population metrics leaving the attenuation of each individual worker unknown.

HPFT system and method developments

Key milestones in the system development, professional recognition of, and regulatory activity surrounding HPFT are illustrated in

Figure **1**. These milestones were selected to illustrate advancements in HPFT methods, standards, and North American professional policy / position statements. First conceptualized in the 1970s [6], three categories of methods to field test attenuation obtained by an end-user for a given fit of a given hearing protector have emerged. These are subjective (psychoacoustic), objective (including microphone-in-real-ear, MIRE), and pressure/seal checks [7]. DiFrancesco et al. [8] provided a timeline highlighting the development of various systems, used as the basis for the following discussion. The first to commercialize was released in 1990 and used a psychoacoustic real ear attenuation at threshold (REAT) method to compare hearing thresholds with open ears to thresholds obtained with the hearing protectors in place. The attenuation of the HPD is evidenced by the shift in hearing thresholds. Secondly introduced, was a microphone in real ear (MIRE) system, commercialized in 2002, which objectively measured the sound pressure levels on either side of an earplug. The next commercially available system came in 2008. This system introduced a different psychoacoustic method, loudness balancing, in which the user matches the loudness of test

signals between both ears for open and occluded conditions. The third category of methods assesses the seal of an earplug by measuring air pressure (for custom earplugs) or low frequency noise levels in the ear canal under an earplug.

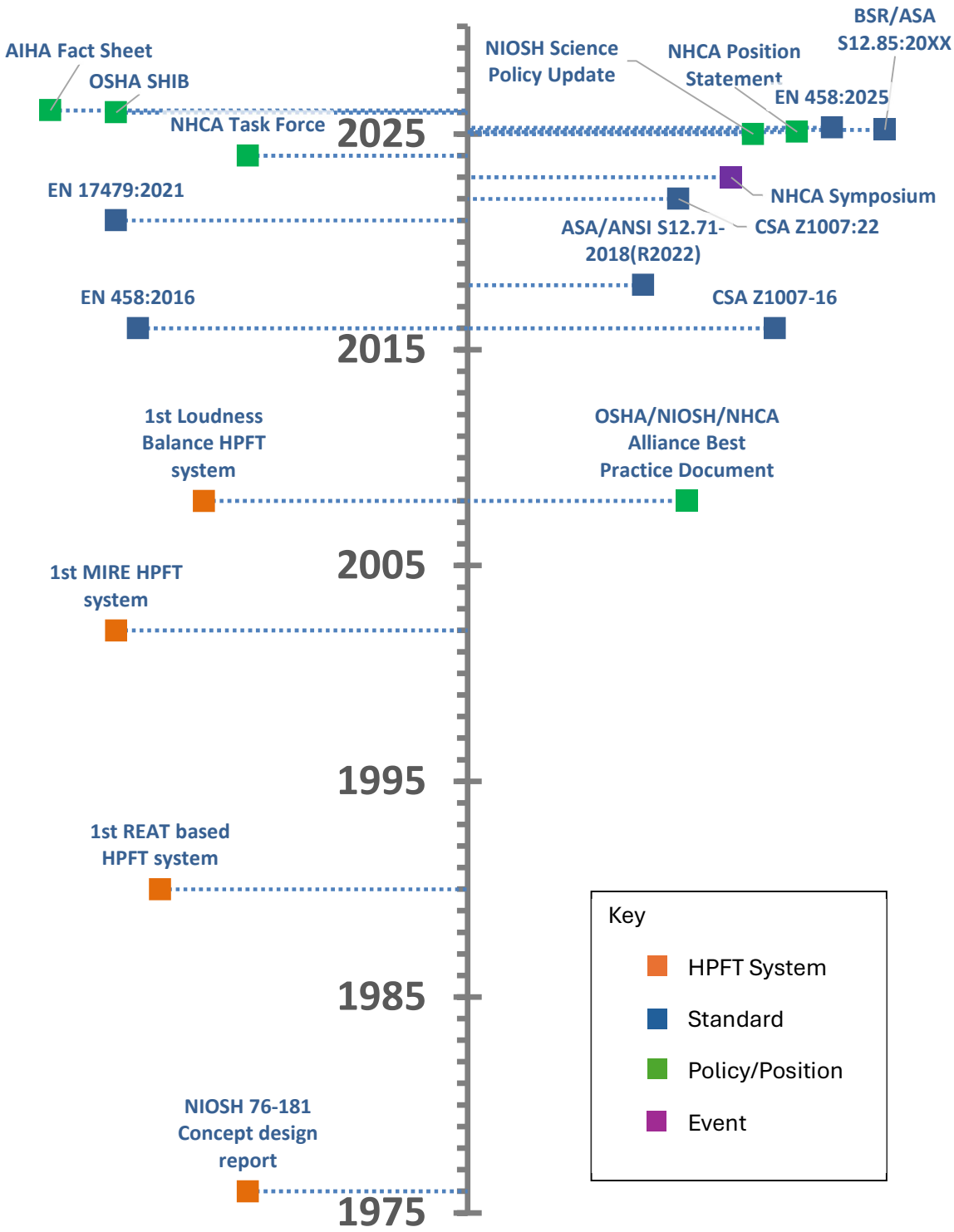

Figure 1: Select milestones in the development of hearing protector fit testing (HPFT).

The term personal attenuation rating (PAR) was introduced during the early development of the various HPFT methods. PAR can be an outcome of a HPFT, depending on the method or system used. Like the HPD labeled attenuation ratings discussed above, the PAR is calculated from attenuation data at multiple frequencies to represent the overall reduction in sound levels as a single numerical value.

Best practice recognition

HPFT was recognized as a best practice in 2008 by an Occupational Safety and Health Administration (OSHA) Alliance with the National Institute for Occupational Safety and Health (NIOSH) and the National Hearing Conservation Association (NHCA) [9]. The *Best Practice Bulletin: Hearing Protection-Emerging Trends: Individual Fit Testing* highlighted many benefits of HPFT and elevated the recognition of HPFT. Within the last ten years, multiple professional organizations and standards bodies have written supportive position statements and recommendations to include HPFT in hearing loss prevention programs.

Research studies

Since various fit test methods and commercialized systems have become readily available, the body of research using these systems has grown. While it is not the intent of this paper to provide an extensive literature review, it is important to note that evidence-based studies inform standards development and regulatory decisions. Some representative studies [10–16] include the following common themes:

1. A wide range of PAR values are achieved across a population of workers for the same model of HPD,
2. A wide distribution of PAR values is seen for multiple types of earplugs and an over-the-head style earmuff,
3. A significant portion of a given workforce does not achieve the attenuation expected based on the single number attenuation labeled value, and
4. PAR values significantly improve after HPFT intervention and training and while a portion of subjects experience some attrition of the PAR value, there is statistically significant improvement compared to the baseline, even after 6 - 12 months.

Distinct from these studies is a recent publication investigating the link between PAR and hearing threshold change, as defined as the Standard Threshold Shift (STS) with more than 1800 military service personnel participants. The authors call out this important finding: the service members with the lowest PARs exhibited the highest STS rates. These results support the importance of early identification of 0 dB and low PAR values to help reduce auditory risk [17].

Standardization

Along with the increase in HPFT systems and HPFT implementation, the increased need for guidance through standardization was recognized. A revision to the EN 458 standard, *Hearing protectors – Recommendations for selection, use, care and maintenance – Guidance document*, was issued in 2016 [18]. Updates included a new informative annex describing fit check methods. Further revision in 2025 [19] reinforced the importance of HPFT by adding definitions of fit testing, PAR, and references to EN 17479. Canada introduced HPFT in 2016

into a new CSA Z1007 standard, *Hearing loss prevention program (HLPP) management* [20]. A section described HPFT and how it can be used in hearing loss prevention programs to verify attenuation achieved by individual workers. A revised version of the standard was issued in 2022 and further expanded the HPFT section to allow PAR to be used as a method when selecting and assigning HPDs [21].

As with other hearing conservation related measurements, such as noise exposures and audiometric testing, the need for standardization of HPFT systems became apparent. For example, Murphy demonstrated that PAR values, calculated according to the approaches of six different HPFT systems using the same set of attenuation data, ranged from 12 dB to 20 dB [22]. The HPFT systems also differed in how the uncertainty of the PAR measurement was reported.

To address this need, the ASA/ANSI S12 (Noise) Committee Working Group 11 created the first standard for HPFT system manufacturers, ASA/ANSI S12.71-2018 (R2022) *American National Standard Performance Criteria for Systems that Estimate the Attenuation of Passive Hearing Protectors for Individual Users* [23]. This standard categorizes the types of fit-test systems and provides performance criteria for each type to enable accurate measurements and transparent reporting of results. The premise of this standard is that fit-test systems be evaluated by comparing their attenuation estimates to attenuation measured using the laboratory "gold standard," REAT method.

A further contribution of the S12.71 standard is to define PAR as a metric to be directly subtracted from an A-weighted noise exposure / sound level, thus making it simple to apply. The standard also provides a method to determine the uncertainty of PAR. Note that the standard includes systems that do not generate PAR values but rather report only pass/fail indicators. Prior to standardization, there was no consensus among HPFT systems regarding use of either A- or C-weighting nor consistent handling of uncertainty. Conformance with the standard helps to increase transparency and comparability of results.

The first European standard intended for the users of HPFT is EN 17479:2021 *Hearing protectors – Guidance on selection of individual fit testing methods* [24]. This standard defines six different test methods: MIRE, two types of REAT methods using audiometric testing protocols, loudness balance, acoustic leakage, and air leakage methods. This standard was informed by the DGUV Guideline 212-003 *Measuring systems for determining the individual protective effect of hearing protection* [25]. Various test methods and procedures were evaluated with guidance for the user when selecting a system to implement HPFT.

EXPANDING LANDSCAPE

There has been a proliferation of publications, policies, position statements, and standard updates around the globe in recent years. At least 13 countries have language about use of HPFT ranging from North America, South America, China, Southeast Asia, Russia, and Europe in either standards or guidance documents. Active standards and/or regulatory revisions are currently underway in other countries. An itemized list of jurisdictions and their associated documents referencing HPFT, to the best of the authors' knowledge as of the publication of this paper, are detailed in **Fejl! Henvisningskilde ikke fundet.**.

In 2023, the first ever International Symposium on Hearing Protector Fit Testing was held, bringing together health and safety professionals, researchers, academicians, manufacturers, and students from seven different countries for two days of presentations and discussions [26]. Outcomes of this symposium are documented in a series of five articles published in the Proceedings of Meetings on Acoustics [27–31].

Table 1: Known standards and regulations from thirteen countries or jurisdictions related to hearing protection devices and HPFT. Table adapted from Wells et al. [27].

Jurisdiction	Reference	Title
Argentina	IRAM 4125: 2020	Recommendations for selection, use, care, and maintenance Guidance Document
Australia/New Zealand	Code of Practice	Managing Noise and Preventing Hearing Loss at Work, July 2020
Brazil	Fundacentro 2018	Guide to minimum guidelines and parameters for the preparation and management of HCP
Canada: Province, Territory, or Federal	CSA Z94.2-14 (R2024)	Hearing protection devices - Performance, selection, care, and use
	CSA Z1007:22	Hearing Loss Prevention Program Management
	Province of Alberta	Occupational Health and Safety (OHS) Code, Part 16
China	GB 23466-2025 (implementation 9-01-2026)	Selection, use and maintenance of hearing protective equipment
	NHC GBZ 331-2024	Specification for occupational health technical service
Europe	EN 458:2025	Hearing protectors - Recommendations for selection, use, care and maintenance - Guidance document
	EN 17479:2021	Hearing protectors - Guidance on selection of individual fit testing methods
Germany	German Ministry for Labour and Social Affairs	TRLV Noise Part 3: Noise Protection Measures
	DGUV 212-003	Measuring systems for determining the individual protective effect of hearing protection
Italy	UNI 9432:2011	Acoustics - Determination of the level of personal exposure to noise in the workplace
	D.Lgs.81/08	2023 General Health and Safety Law (amended in Dec.2021 to require EN 458)
Malaysia	DOSH Guideline MONRHD 2021	Malaysia DOSH Guidelines on Management of Occupational Noise-Related Hearing Disorder
Russia	The Association of PPE Developers, Manufacturers and Suppliers	Methodological recommendations for the selection and use of personal hearing protection
United States	ANSI/ASSP A10.46 – 2020	Hearing Loss Prevention for Construction and Demolition Workers
	ASA/ANSI S12.71-2018 (R2022)	Performance criteria for systems designed to estimate the attenuation obtained by individual users of passive hearing protectors
	DA PAM 40-501	Army Hearing Program
	DODI 6055.12	Hearing Conservation Program (HCP)
Uruguay	UNIT 1351:2021	Hearing protection-Recommendations for selection, use, care, maintenance - Guidance Document
Venezuela	Standard NTF 871	Hearing protectors
	Standard NTF 1565	Hearing Conservation Program, Venezuela

Since then, US based professional organizations have promoted HPFT as a best practice, issuing position statements and/or developing training programs to educate their stakeholders. Some examples include:

- National Hearing Conservation Association Position Statement [32]
- Council for Accreditation in Occupational Hearing Conservation HPFT Training Course [33]
- National Hearing Conservation Association/National Occupational Research Agenda Hearing Loss Prevention Cross-Sector Council Guidance Document [34]
- American Industrial Hygiene Association Hearing Protector Fit Testing Overview Document [35]
- International Safety Equipment Association Position Statement [36]

A significant policy advancement was issued by the National Institute for Occupational Safety and Health in 2025 [37]. Based on strong evidence that HPFT is a better predictor of hearing protector attenuation on individual workers than derated NRRs [38,39], NIOSH officially superseded its 1998 NRR derating scheme [5] with a recommendation to conduct quantitative, individual HPFT. It states that employers should integrate individual HPFT into occupational hearing conservation programs.

REGULATORY REQUIREMENTS

HPFT has also entered the realm of regulatory requirements specifically naming HPFT as an attenuation verification tool. In the EU 2016/425 Personal Protective Equipment regulation [40] harmful noise was elevated to the highest risk, category III. HPFT is recognized within the supporting documentation to the regulation as a method for ensuring appropriate attenuation. A Germany technical rule, TRLV Noise Part 3 [41], specifies custom-molded earplugs have a functional check, such as a seal check, upon delivery and regularly thereafter. In the 2023 update to the Occupational Health and Safety (OHS) Code, Part 16 [42], the Province of Alberta, Canada specifies that hearing protectors be fit tested in accordance with CSA Z94.2 [43]. The latest revision of this Canadian standard, *Hearing protection devices - Performance, selection, care, and use*, is currently being balloted with publication expected in 2026. It aligns with CSA Z1007 by recognizing PAR as one of the accepted methods for assigning HPDs.

Also in 2023, the US Department of Defense instituted mandatory HPFT as part of a comprehensive hearing conservation program for at-risk personnel who meet at least one of these specific conditions [44]:

1. Noise exposure unknown or noise exposure greater than or equal to 95 dBA 8-hour time-weighted average (TWA),
2. Identification of a positive Standard Threshold Shift in hearing, either permanent or temporary,
3. Physical change to the ear canal which causes poor HPD fit,
4. Primary type of fitting hearing protector becomes unavailable, or
5. Identification of an early warning hearing threshold shift: 15 dB shift at a single frequency of 1000, 2000, 3000, or 4000 Hz.

The DoDI 6055.12 *Hearing Conservation Programs* instruction includes additional details regarding how HPFT is conducted to account for multiple test environments, data collection requirements, and special HPD applications [44].

The US OSHA requirements in 29 CFR 1910.95 [45] for occupational hearing conservation have not changed since they were promulgated in 1983; however, 1910.95(i)(5) stipulates that the employer shall ensure proper initial fitting and supervise the correct use of all hearing protectors. Further, in section 1910.95(j), employers are required to evaluate hearing protector attenuation.

Since becoming a viable tool, OSHA has shown support in using HPFT as a training tool and to help meet the existing HCP requirements through a Letter of Interpretation [46], updated information in the *OSHA Technical Manual* chapter on noise [47], and most recently, a *Safety and Health Information Bulletin* on hearing protector fit testing [48]. Indirectly demonstrating its support of HPFT, OSHA requires its own field personnel to undergo annual HPFT as outlined in the *OSHA Field Safety and Health Management System (SHMS) Manual* [49].

RAISING THE PAR: FUTURE DEVELOPMENTS

Momentum is the product of mass and velocity. The past decade has experienced a rise in the mass of publications, the weight of evidence, and the speed of acceptance. But more work is needed to raise the PAR and affect hearing loss prevention outcomes in the long-term. From a standards development perspective, there are some opportunities to further build foundational standards. From a regulatory perspective, it is generally presumed that mandating HPFT is dependent on the existence of referenceable, evidence-based standards. To that point, a new draft standard, designated BSR/ASA S12.85:20XX *Hearing Protector Fit Testing Program: Methods and Guidance*, is being created; work that is currently led by the NHCA Task Force on HPFT [50]. The scope includes defining the critical elements of a HPFT and differentiating what “shall” and what “can” be included. A key concept is that the HPFT be integrated into a comprehensive hearing loss prevention program supported with actionable intervention while acknowledging the existence of multiple HPFT methods.

Times, technologies, and expectations of HPFT continue to evolve. With a revision of the ASA/ANSI S12.71 standard coming due, there is an opportunity to think about potential updates to the system performance criteria and how to address conditions that did not exist when the standard was first introduced. In terms of technologies, there are now “systems” that allow physical measurements to be made in situ by the hearing protector itself while being worn. There are real-time measurement devices. These introduce new challenges for quantifying and reporting measurement uncertainty, for example, if the worker’s noise spectrum can be measured in real-time, is a spectral uncertainty factor, as it is in the current standard, superfluous? The testing paradigms have changed, moving away from the traditional 1:1 fit-test operator to fit-tested worker ratio, towards a multi-person test station or a self-administered HPFT model. As data collection and aggregation are realized, is there a need for performance criteria around recordkeeping, data security, and privacy concerns? Added measurement capabilities, such as quantifying PAR for combinations of HPD (earplugs and earmuffs worn simultaneously), and application of PAR against impulsive noise values, may need to be considered.

CONCLUSION

HPFT will continue to progress together with the need to accurately quantify individual protected noise exposure in dynamic and challenging sound environments. Collaboration with standards committees, researchers, and health and safety specialists worldwide will be important toward driving consistent, accepted, and standardized practices, raising the PAR for hearing health.

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Non-auditory effects of noise: an overview of the state of the science for the period 2023-2026

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ABSTRACT

Studies continue to link long-term noise exposure to cardio-metabolic disease and neurological outcomes, with growing evidence on mental health disorders and premature death. We used PubMed to search peer-reviewed literature published between 01.2023 and 12.2025. Results were imported into Rayyan, an online tool. Abstract and full text screening were performed by the main authors, with Team 3 volunteers assisting on data extraction. Three study types were identified: original studies, systematic reviews and narrative reviews. Data extraction was performed for the first two. The living review identified 378 papers of which 155 were full text screened. Of these, 28 were flagged as narrative and 2 as bibliometric reviews, and 95 were pushed to data extraction (68 original studies, 27 systematic reviews). Original studies covered various outcomes including cardiometabolic disease, anxiety, depression and mental health, cognition or dementia, birth and pregnancy, respiratory disease, cancer and mortality. The systematic reviews focused on cardiometabolic disease, dementia, pregnancy and cancer; one summarised evidence from LMICs. The narrative reviews were mainly on CVD. The topic of non-auditory health effects of noise is rapidly growing in scope of outcomes and exposures (e.g. hospital noise on patients, music and natural sounds). A living review is an efficient method to regularly, and collaboratively, capture and update the knowledge base to help identify gaps and priority areas for future research.

INTRODUCTION

ICBEN Team 3 on the “non-auditory effects of noise”, focusses on the long-term consequences of both occupational and environmental noise on health. The knowledge base continues to grow, reflecting outcomes across multiple body systems including the cardiovascular, endocrine, respiratory and immune systems. Outcomes of interest also include mental health and wellbeing, children’s health and neurodevelopment (outside of cognitive

and academic performance and behavior, as that falls under Team 4), neurodegeneration, cancer and premature death.

This paper aimed to capture an overview of the recent and emerging research on the non-auditory effects of noise published since the last ICBEN conference covering the between period 01.2023 and 12.2025, by summarising original research and reviews.

METHODS

We used a living review framework to conduct the Team 3 review (Figure 1). This was facilitated using PubMed and Rayyan, a tool for collaborative online reviews.

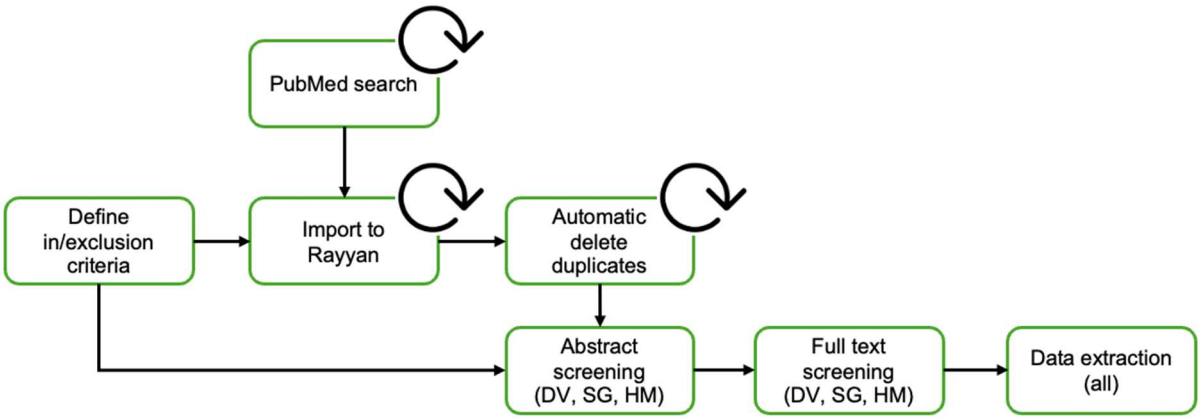

Figure 1: Workflow for the Team 3 review (circular arrows indicate iterative steps)

Using PubMed, we searched peer-reviewed literature published between 01.2023 and 12.2025, following the search strategy used in the EEA report [1], built from the WHO evidence reviews by Clark and Paunovic [2] and van Kempen [3], and underpinning the Environmental Noise in Europe 2025 report [4]. See Appendix 1 for the search string.

The search and subsequent import into Rayyan were conducted iteratively, in total four times during the review period, with the last search on 05.03.2026 to capture any 2025 papers that were released in 2026. Inclusion and exclusion criteria were established within Rayyan to facilitate screening (e.g. exclude animal studies and topics for other ICBEN teams). We applied single screening by three authors (DV, SG, HM) to both the abstract and full text screening stages, using the “maybe” option to identify papers needing a second opinion or discussion.

Data extraction was conducted by all authors which included volunteers from Team 3. Three study types were identified: original studies, systematic reviews and high-level narrative reviews. The latter were compiled in a list. Data extraction was performed for the original studies and systematic reviews, after designing a fit-for-purpose data extraction form. On completion of data extraction, the results were exported from Rayyan as a csv file and checked/harmonised by DV and SG.

RESULTS

The living review identified 378 papers of which 155 were full text screened. Of these, 28 were flagged as narrative and 2 as bibliometric reviews, and 95 were pushed to data extraction (27 systematic reviews and 68 original studies).

Systematic reviews and meta-analyses

The search identified 27 systematic (scoping) reviews (Table 1). While some were strictly focussed on noise exposure, others included noise as one of the environmental factors under review. The studies were from across the globe, with one specifically focussed on low- and middle-income countries [5]. The majority of reviews considered adult populations (93%), with 30% including or focussing on children. As expected, most studies were on transportation or community noise, with a smaller share examining occupational, and relatively fewer on wind turbine, industrial, hospital or indoor noise, or leisure/recreational noise. It should be noted that hospital, indoor, leisure/recreational noise and music were not specifically included in the search string, thus some reviews on these sources may have been missed. The reviews covered a broad range of outcomes ranked by count of occurrence as follows: cardio-metabolic disease, mental health and wellbeing, birth outcomes, neurodegenerative disease, cancer, neurodevelopment, and finally diseases of the respiratory and immune systems. Many of the reviews evaluated the quality of the individual studies, and only 48% included meta-analyses. Most of the meta-analyses were on cardiovascular disease (CVD) [6-12] and diabetes [7, 13-15], depression and anxiety [7, 16], dementia [17], cancer [18] and birth outcomes [7]. See Appendix 2 for a descriptive visual overview of the reviews.

Cardio-metabolic disease

Road traffic noise showed a small but robust increase in the risk of incident cardiovascular disease (~1-5% per 10 dB) [6, 8, 10, 11], including ischaemic heart disease (IHD), myocardial infarction (MI), stroke, and heart failure. For heart failure, the risk was ~5-7% per 10 dB [8, 9, 11]. Aircraft noise also showed associations with cardiovascular disease, while evidence for railway noise was generally weaker. Several reviews reported modest associations between noise and type 2 diabetes in the range of ~6-8% per 10 dB in residential settings [13, 15] and higher in occupational settings [14].

Mental health and cognition

The second major area of consistent evidence was for mental health and cognition. The reviews showed that noise is associated with higher levels of depression and anxiety [7], with noise annoyance and sleep disturbance frequently identified as mediators [19]. Reviews conducted for clinical settings, on patients or staff, further showed that elevated noise was associated with anxiety, delirium, and physiological stress responses [20, 21]. Growing evidence also showed chronic noise exposure is associated with cognitive decline and increased risk of dementia, as well as poorer cognitive performance in children [17, 22].

Other health endpoints

Findings for other health domains were more mixed. Evidence for cancer was inconsistent due to heterogeneity in the studies. Some positive associations were found with breast cancer (road traffic noise) and acoustic neuroma (occupational or leisure noise) [23]. The pooled estimates for breast cancer, however, were largely null (no other cancers were meta-analysed) [18]. Perinatal outcomes (e.g., birth weight, preterm birth) showed limited or non-significant associations [7, 24], while for maternal health one review on occupational noise suggested a possible association with maternal hypertension [25].

A list of the narrative and bibliometric reviews including noise as exposure is provided in Appendix 3.

Original studies

After screening, 68 original studies were retained with the same broad range of outcomes as in the reviews (Table 2). Most studies were on the general population (65%), followed by occupational groups (22%), women in nurses' health studies (7%), and patient groups (6%). The majority of studies considered road traffic noise, followed by occupational noise and other transportation noise, with fewer studying hospital noise, industrial noise, and wind turbine

noise. The studies covered a broad range of outcomes ranked by count of occurrence as follows: cardiometabolic disease, mental health and wellbeing, mortality, neurodegenerative disease, and several studies each on renal disease, cancer, immune response and the respiratory or musculoskeletal systems. See Appendix 2 for a descriptive visual overview of the studies.

Cardio-metabolic disease

Multiple occupational and community studies reported higher blood pressure (BP) and hypertension was correlated with noise exposure [26-29], with nighttime aircraft noise particularly relevant for incident hypertension [30, 31]. Several studies found that noise was associated with worse cholesterol ratios and metabolic scores [32, 33], and increased BMI and visceral fat [34, 35]. Within a healthy population, Wicki et al. [36] demonstrated that noise exposure was associated early indicators of cardiometabolic risk. One study showed that BP measured in noisy public spaces closely matched readings in a quiet office [37], suggesting noise does not invalidate BP screening.

Most studies reported higher risks of IHD, MI, stroke, atrial fibrillation, heart failure, and CVD mortality with road traffic and railway noise. Pyko et al. [38] reported an increase of incident IHD and MI at thresholds around 55 dB Lden, while Yang et al. [39] found the association between road noise and incident heart failure was partly mediated by prior MI (~12%). Road traffic noise was also found to be associated with an increase intracerebral haemorrhage risk, particularly in low-greenspace areas [40], extending cerebrovascular evidence beyond ischaemic stroke. Self-reported composite CVD and specific diagnoses (angina, heart failure) were consistently higher in occupational noise-exposed groups [41]. Aircraft noise stood out for its associations with stroke and IHD prevalence [42], CVD hospitalizations during evening and early morning hours [43, 44], and recurrent CVD events and mortality in patients with pre-existing disease [45]. Experimental evidence confirmed acute endothelial dysfunction after nighttime exposure to noise events [46].

Mental health and cognition

New studies consistently linked noise to depression, anxiety, stress, and poor wellbeing, with several reporting stronger associations in younger adults, women or specific occupational groups. Several studies, using different designs, showed associations between noise and risk depression [47-49], and anxiety was found to partially mediate the relationship between hospital noise and self-rated health in patients [50]. One study demonstrated that perceived noise predicted mental health more strongly than modelled noise [51], highlighting the role of annoyance and sensitivity. Clinical outcomes broadened the evidence base, with Nobile et al. [52] reporting that road traffic noise associated with increased risk of incident schizophrenia spectrum disorders, depression and anxiety. An experimental study showed noise could undermine the restorative effects of natural soundscapes [53], and occupational studies showed noise associated with poorer mental health among emergency department vs. general inpatient department staff [54] and higher stress among traffic police vs. office-based police [55].

Evidence for cognitive effects was mixed. Several studies found that noise was associated with lowered cognitive scores, accelerated cognitive decline, or increased risk of cognitive impairment, no dementia (CIND) [56-58]. Mediation analyses highlighted that the association for occupational noise and cognitive impairment was mainly mediated via sleep disturbance and tinnitus [57]. Structural Magnetic Resonance Imaging (MRI) studies provided novel findings; Binter et al. [59] found prenatal road noise exposure associated with lower fractional anisotropy suggesting early-life neurodevelopmental effects, while Soeterboek et al. [60] reported that environmental noise associated with structural markers of brain damage in adults.

Other health endpoints

Regarding pregnancy and perinatal outcomes, new studies showed that occupational noise >80 dB increased gestational diabetes and mild pre-eclampsia [61], and that occupational noise increased blood pressure, glucose, lipids, heart rate, and even foetal size [28]. One study found a suggestive association between high road traffic noise and postpartum depression [62], extending possible noise effects into the postpartum period.

Several studies explored less-common outcomes. In the Danish Nurse Cohort, road traffic noise was associated with increased acute lower respiratory infections, especially above a 57 dB threshold and among nurses with asthma or lower socioeconomic status (SES) [63]. High community noise was associated with thyroid nodules [64], road traffic noise was not associated with sensorimotor polyneuropathy [65], and occupational noise was associated with increase self-reported osteoarthritis and rheumatoid arthritis [66].

Mortality

Large cohorts with detailed exposure assessment confirmed road traffic (and to a lesser extent railway) noise associations with natural-cause, CVD, respiratory, and cancer mortality [67-69] and non-type 1 diabetes mortality [15], with effects persisting at relatively low exposure levels. A particularly novel finding was the association between noise and suicide [70].

DISCUSSION

The current literature highlights noise as a significant multisystem stressor, with the most consistent evidence still for cardiovascular and mental health outcomes. New studies largely reinforce earlier evidence that environmental noise increases cardiovascular risk, while adding detail on thresholds, time-of-day vulnerability and specific endpoints. Overall, the evidence strengthens the link between noise and mental health, with new insights into clinical diagnoses and perception-based pathways. New studies also broaden the pregnancy literature beyond birth outcomes toward maternal metabolic and cardiovascular responses. Overall, the evidence on noise and mortality is strong as it continues to expand into new cause-specific domains.

Regarding broad trends, research on the non-auditory effects of noise was predominantly concentrated in the west but as demonstrated in this review has gradually spread to Asian and other regions. In addition, noise is less so regarded as an independent factor; it is increasingly considered alongside other environmental exposures to explore the combined impacts of multiple environmental factors on human health (see Team 8 review on “interactions with other agents and contextual factors”).

In the future, adding a study quality component to ICBEN Team reviews would provide more clarity on the strengths and limitations of the noise and health literature.

Table 1: Systematic and scoping reviews, sorted by Author-Year

Author	End of search period	N study*	N pop*	Countries*	Pop	Noise source(s)	Setting	Endpoint(s)	Individual study quality	Meta-analysis	Overall quality of evidence
Abbasi 2023 [23]	Apr 2022	19	148 – 3.5m	AU, BR, CA, DE, DK, FI, FR, IL, IT, JP, NO, NZ, SE, UK, US	AC	4-6, 10	1, 2	1, 4	JBI	no	no
Au-Yeung 2024 [71]	Feb 2024	11	10 – 193	Asia, Eur, N.Am	A	11	1	6	n/a	no	n/a
Brown 2025 [6]	Oct 2024	9	161k – 3.6m	Eur, N.Am	A	1-3, 8	1	2	ROBINS-E	yes	no
Chen 2023 [5]	Nov 2021	58	1.5m	BG, BR, CN, IN, IR, MX, NG, NM, MY, PK, RS, TH, VN, ZA	AC	1-8	3	1, 2, 5, 7	ROB	no	NG
Chen 2023 [7]	Nov 2021	23	n/r	n/r	AC	1-3, 5	1, 2	1-3, 5, 8	AMSTAR-2	yes	GRADE
Febriyanto 2024 [72]	Jan 2023	16	290k	AG, BE, BR, DE, DK, FR, IN, IR, LR, NO, NZ, TH, UK, US	A	5	2	5, 13	no	no	no
Fu 2023 [8]	Apr 2022	23	420 – 8.6m	CA, DK, GR, IT, NL, NO, SE, UK	A	1-3	1	2	NOS	yes	no
Grocott 2025 [19]	May 2023	14	257 – 354k	BG, CA, CH, DK, NL, PK, UK, US	A	1-3, 6, 8	1	5, 13	ROB	no	GRADE
Hu 2025 [16]	Mar 2024	11	16k	AU, DE, IT, JP, KR, NL, NO	A	1-3, 6	1, 2	5	NOS	yes	no
Ibrahimi Asllani 2025 [22]	Jul 2025	100	420 – 50m	BG, BR, CA, CH, CN, DE, DK, ES, FI, FR, GR, IE, IT, KR, LB, NL, NO, SE, UK, US	AC	1-3, 6, 8	1	1, 2, 6, 7	n/a	no	n/a
Jones 2025 [17]	Nov 2023	2	2.1m – 77.9m	CA, DE, DK, ES, SE, UK, US	A	1-2, 5, 6	1, 2	6	AMSTAR-2	yes	AMSTAR-2
Le Lous 2023 [73]	Dec 2022	2	30 – 440	UK, US	A	9	4	13	no	no	no
Lee 2023 [74]	Jul 2022	36	40 – 0.5m	AU, BG, DE, FI, FR, GR, IN, IR, IT, KR, NL, SE, SK, UK, US	AC	1-3, 5-10	1, 2, 4	1-6, 8-10	no	no	no
Li 2025 [21]	Oct 2024	10	1,485	CH, CN, IN, IT, TR, UK, US	A	9	2, 4	13	JC, NOS	no	no
Liu 2023 [13]	Feb 2022	10	5m	CA, CH, DE, DK, GR, SE	A	1-4	1	3	NG, NOS	yes	GRADE
Liu 2025 [9]	Jul 2024	8	8.6m	CA, CH, DK, NL, UK	A	1	1	1, 2	ROBINS-E	yes	GRADE
Menkin 2025 [10]	Dec 2023	53	364k – 29.4m	BR, CA, CH, DE, DK, ES, FR, GR, HK, IT, NL, NO, SE, UK, US	A	1-3	1	1, 2	ROB	yes	GRADE
Momen 2025 [18]	Feb 2025	19	1,759 – 3.1m	DE, DK, NL, SE, US	AC	1-3, 6	1	1, 4	ROB	yes	GRADE
Münzel 2024 [11]	mid-23	30	420 – 10.5m	CA, CH, DE, DK, FR, IT, NL, SE, UK, US	A	1-3	1	1, 2	AMSTAR-2	yes	AMSTAR-2
Rahmanian 2023 [14]	Aug 2022	12	300 – 1.1m	BR, BU, CA, CN, DK, SE, SK, TN	A	5	2	1, 3	ROB	yes	GRADE
Sebastian 2025 [12]	Dec 2024	34	35.5m	AU, BR, CH, DE, FR, GR, IT, KR, NL, PL, SE, TW, UK, US	A	2	1	1, 2	ROB	yes	GRADE
Solvik-Olsen 2025 [75]	Dec 2023	5	10 – 140	CA, FR, NZ, SE, UK	C	1-2	6	2, 13	CASP	no	no

Author	End of search period	N study*	N pop*	Countries*	Pop	Noise source(s)	Setting	Endpoint(s)	Individual study quality	Meta-analysis	Overall quality of evidence
Sonoda 2025 [20]	Jan 2025	28	11 – 26k	AU, CA, CN, ES, FR, ID, IR, JO, KR, MX, NL, PL, PT, SA, TR, TW, US	A	9	1, 4	5, 13	n/a	no	n/a
Tabaei 2025 [76]	May 2025	22	36m	BR, BU, CH, CN, DE, NL, IR, IT, SE, UK	N/Avail	6	1, 2	1, 2	AMSTAR-2	no	GRADE
Ulin 2024 [25]	Dec 2023	25	600 – 1.4m	BU, CA, DE, DK, FR, NL, SE, TR, UK, US	A	5, 6	1, 2	1, 3, 5, 8	no	no	no
Vienneau 2024 [15]	Nov 2023	14	420 – 4.1m	CA, CH, DE, DK, ES, GR, SE, UK	A	1-4, 6	1	1, 3	n/a	yes	n/a
Wies 2024 [24]	Dec 2022	3	311 – 9.6m	CA, DK, DE, ES, FI, GR, IT, KR, NL, NO, RS, SE, UK, US	AC	1	1, 5	2, 8	R-AMSTAR-2	no	R-AMSTAR-2

*Some N study, N pop and Countries may be overestimated, e.g. in reviews exposures other than noise. For N: m = million; k = thousand.
n/a = not applicable; n/r = not reported
Countries: AG = Antigua and Barbuda; AU = Australia; BE = Belgium; BR = Brazil; BG = Bulgaria; CA = Canada; CH = Switzerland; CN = China; DE = Germany; DK = Denmark; ES = Spain; FI = Finland; FR = France; GR = Greece; HK = Hong Kong; ID = Indonesia; IE = Ireland; IL = Israel; IN = India; IR = Iran; IT = Italy; JO = Jordan; JP = Japan; KR = South Korea; LB = Lebanon; LR = Liberia; MK = Macedonia; MX = Mexico; MY = Malaysia; NG = Nigeria; NL = Netherlands; NO = Norway; NZ = New Zealand; PK = Pakistan; PL = Poland; PT = Portugal; RS = Serbia; SA = Saudi Arabia; SE = Sweden; SK = Slovakia; TH = Thailand; TN = Tunisia; TR = Turkey; TW = Taiwan; UK = United Kingdom; US = USA; VN = Vietnam; ZA = South Africa

Pop: Populations: A = Adults; C = Children

Noise source(s): 1 = Road traffic; 2 = Aircraft; 3 = Railway; 4 = Transportation; 5 = Occupational; 6 = Community/Environmental; 7 = Industrial; 8 = Wind Turbines; 9 = Hospital; 10 = Leisure/Recreational; 11 = Indoor

Setting: 1 = Residential; 2 = Occupational; 3 = Non-occupational; 4 = Indoor; 5 = School; 6 = In-transit

Endpoint(s):
1 = Mortality (cause-specific, natural-cause);
2 = Cardiovascular system (stroke, cerebrovascular disease, coronary heart disease, ischemic heart disease, angina, myocardial infarction, atrial fibrillation, heart failure, hypertension, flow mediated dilation (FMD) of brachial artery, heart rate, Framingham score, systolic and/or diastolic blood pressure, ECG abnormalities);
3 = Endocrine system (hyperglycaemia, obesity, diabetes, pre-diabetes, maternal hypertension, gestational diabetes);
4 = Cancer (all-site cancer, breast cancer, childhood cancer, colon cancer, colorectal cancer, lung cancer, prostate cancer, acoustic neuroma, Hodgkin lymphoma, non-Hodgkin lymphoma, vestibular nerve schwannoma);
5 = Mental health (depression, anxiety);
6 = Neurodegenerative diseases (dementia, Alzheimer's disease, Vascular dementia, memory, behavioural and psychological symptoms of dementia, cognitive impairment);
7 = Neurodevelopment (cognitive function, brain structure and biomarkers);
8 = Perinatal and birth outcomes (embryonic growth, foetal growth, foetal development, congenital anomalies, low birth weight, gestational age, SGA, preterm birth);
9 = Immune response (cytokines, c-reactive protein, cortisol);
10 = Respiratory system (asthma, bronchitis);
11 = Renal function (biomarkers for blood urea nitrogen, 24-hr urinary albumin excretion rate, serum creatinine, 4-hour urine protein);
12 = Musculoskeletal system (rheumatoid arthritis, osteoarthritis);
13 = Well-being in general/patient populations (well-being, health-related quality of life, headache, fatigue, stress, neonatal stress, pain profile/discomfort, cortisol levels, delirium, pain, unplanned readmission)

Individual study quality: (R)-AMSTAR 2 = (Revised) A MeaSurement Tool to Assess Systematic Reviews, version 2; CASP = Critical Appraisal Skills Programme checklist; JBI = Joanna Briggs Institute critical appraisal tool; JC = Jadad scale for RCTs; NOS = Newcastle Ottawa scale; NG = Navigation guide; ROB = Risk of Bias tool; ROBINS-E = Risk Of Bias In Non-randomized Studies - of Exposures

Overall quality of evidence: (R)-AMSTAR 2 = (Revised) A MeaSurement Tool to Assess Systematic Reviews, version 2; GRADE = Grading of Recommendations Assessment, Development and

Evaluation; NG = Navigation guide

Table 2: Original papers, sorted by Author-Year

Author	Country	Design	Population Characteristics			Noise source(s)	Exposure method(s)	Exposure metric(s) (Time window(s))	Endpoint(s)
			N	Sex / Age (mean, min, or range)	Pop group(s)				
Bartoskova Polcrova 2025 [34]	CZ	CS	2,031	55% F / 25-64 y	1	4	1	Lden	3
Bartoskova Polcrova 2024 [32]	CZ	CS	2,154	55% F / 25-64 y	1	4	1	Lden	3
Binter 2024 [59]	NL, FR	CS	2,725 (NL); 95 (FR)*	50% F / 9-12 y	1	1	1	Lden (pregnancy, childhood)	6
Bozigar 2024 [35]	US	CO	74,848	100% F / 50 y	1, 3	2	1	Ldn ‡	3
Buteau 2023 [77]	CA	CO	~899,300	51% F / ≥45 y	1	6	1	LAeq24hr	2
Cadman 2024 [62]	DK, ES, FR, GR, IT, NL, NO, UK	CO, MA	23,956	100% F / 15-50 y	1	1	1	Lden	5
Chen 2025 [33]	CN	CS	854	85% M / 36 y	3	5	2, 4	LAeq8hr	3
Du 2024 [78]	CN	CS	705	95% M / Adults	3	5	2	LAeq8hr; CNE; kurtosis	2
Dzhambov 2025 [42]	BG	CS	4,640	54% F / 18-90 y	1	1-3	1	Lden	2
Gilmour 2024 [53]	UK	QE	68	69% F / 18-42 y	1	6	1	3 x 1-min stressor followed by 3-min soundscape video	5, 13
Gómez González 2023 [79]	ES	TS (ECO)	67,225	MF / all ages	1	6	2	Lday, Lnight	5
Gomm 2023 [51]	CH	CS	5,729	MF / 18-94 y	1	1, 7	1, 5	Lden	5
Gonçalves Soares 2024 [80]	UK, FI*, FR, NL	RM	5,095	50% F / 3-26 y	1	1	1	Lden, Lnight	2
Gong 2024 [43]	UK	CCO (ECO)	1,912,035 postcodes	MF / all ages	1	2	1	Lday, Lnight	1, 2
Gu 2023 [40]	UK	CO	402,268	55% F / 57 y	1	1	1	Lden	2
Guo 2024 [41]	US	CS	6,266	52% F / ≥20 y	3	5	5	exposure (Y/N), duration, intensity	2
Hahad 2023 [46]	DE	CCO	275	60% M / 43 y	1	2, 3	3	number of night events	2, 9
Herder 2023 [65]	DE	CO	423	50% F / 68 y	1	1	1	LAeq24hr, Lnight	3, 6, 12
Hu 2023 [81]	UK	CO	390,834	55% F / 56 y	1	1	1	Lden	3
Huang 2024 [56]	CN	CS	614	96% M / 34 y	3	5	2	LAeq8hr, CNE	6

Author	Country	Design	Population Characteristics			Noise source(s)	Exposure method(s)	Exposure metric(s) (Time window(s))	Endpoint(s)
			N	Sex / Age (mean, min, or range)	Pop group(s)				
Huang 2025 [57]	CN	CS	339	98% M / 25 y	3	5	2	LAeq8hr, CNE, kurtosis-adjusted CNE	6
Ishigami 2025 [37]	US	QE	108	59% M / 56 y	1	6	2	Short-term mean (unclear period)	2
Itzkowitz 2023 [44]	UK	CCO	6,300,000	58% M / 57% ≥ 65 y	1	2	1	Lden, Lday, Leve, Lnight, LAeq24hr (1 day before event), 8 distinct time periods throughout 24 hr	1, 2
Jin 2024 [82]	CN	CS	1,125	79% M / Adults	3	5	2	Lex8hr, Lex40hr	2
Jin 2024 [67]	US	CS (ECO)	1,168,510	53% M / 71 y	1	6	1	Ldn, L50day, L50night	1, 2
Lin 2023 [83]	TW	CS	3,191	51% F / 30-70 y	1	1	1	LAeq24hr	5
Liu 2025 [84]	CN	CS	4,530	79% M / 21-60 y	3	5	2	LAeq8hr	2
Maekawa 2025 [85]	JP	CS	394	56% F / all ages	1	2	2	exposure (high/low/none)	13
Melese 2023 [26]	ET	CS	300	94% M / ≥18 y	3	5	2	LAeq8hr	2
Moroe 2025 [86]	ZA	CS	86	100% M / ≥18 y	3	1,5	5	frequency of exposure, exposure duration	3
Nguyen 2023 [30]	US	CO	18,783	100% F / 50-79 y	1	2	1	Ldn, Lnight	2
Niedermayer 2025 [87]	DE	CS	11,101	49% F / 52 y	1	1	1	Lden	3
Nobile 2023 [52]	IT	CO	1,733,331	55% F / 56 y	1	1	1	Lden	5
Olbrich 2023 [45]	DE	CO	737	77% M / 59 y	2	1-3	1	Lden, Lday, Lnight	1, 2
Pasanen 2025 [61]	DK, FI, NO, SE	CS	373,184	100% F / 32 y	3	5	4	LAeq8hr	3
Peer 2024 [88]	IN	CS	1,623	54% M / 18-75 y	1	1	1, 2 †	Lden	2
Peters 2025 [31]	US	CO	162,109	100% F / 59 y (NHS), 40 y (NHSII)	1, 3	2	1	Ldn‡, Lnight‡	2
Pyko 2023 [38]	DK, SE	CO	132,801	63% F / 55 y	1	1-3	1	Lden, most exposed façade (5 yr)	1,2
Ramadan 2025 [89]	EG	CS	80	100% M / 49 y	3	5	2	LAeq8hr (1 day)	2, 3, 5, 6, 13
Ravindra 2025 [55]	IN	CS	200	100% M / 39 y	3	1,5	2	LAeq30min at peak and non-peak hours	2, 5, 13
Ren 2025 [54]	CN	CS	226	54% F / ≥ 18 y	3	9	2	Lday, Lnight (1 day)	5, 13

Author	Country	Design	Population Characteristics			Noise source(s)	Exposure method(s)	Exposure metric(s) (Time window(s))	Endpoint(s)
			N	Sex / Age (mean, min, or range)	Pop group(s)				
Roswall 2023 [90]	DK, FI, SE	CO	155,203	65% F / ≥ 18 y	1	1-3	1	Lden (1 and 5 yr)	4
Shen 2025 [50]	CN	CS	270	50% F / ≥ 60 y	2	9	2	LAeq24hr (1 day)	5, 13
Shi 2023 [47]	HK	CO	13,401	53% F / ≥15 y	1	1	1	Ldn	5, 13
Soeterboek 2025 [60]	NL	CS	4,023	51% F / 40-75 y	1	1-3, 7, 8	1, 5	Lden (4 yr), Exposure (Y/N)	6
Sørensen 2023 [91]	DK	CO	286,151	54% F / ≥16 y	1	1, 3	1	Lden at most & least exposed façade (10 yr)	3
Sørensen 2023 [68]	DK	CO	2,613,731	51% F / >50 y	1	1,3	1	Lden at most & least exposed façade (10 yr)	1, 2, 4, 10
Stucki 2024 [92]	SE	CO	20,407	100% F / 62 y	1	1	1	Lden (5 yr)	2
Tuffier 2024 [93]	DK	CO	25,233	100% F / 53 y	1,3	1	1	Lden	6
Veber 2023 [94]	DK, NO, SE, IS, EE	CS	13,096	53% F / 38-66 y	1	1	5	exposure (Y/N)	3
Vienneau 2023 [69]	CH	CO	4,188,175	52% F / 52 y	1	4	1	Lden	1, 2, 10
Vienneau 2024 [15]	CH	CO, MA	4,136,220	52% F / ≥30 y	1	1-3	1	Lden (5 yr)	1, 3
Wang 2023 [27]	CN	CS	4,746	73% M / 34-49 y	3	5	2	LAeq8hr	2
Wang 2025 [48]	US	CS	17,712	51% F / 18-69 y	1	5	5	exposure duration	5, 9
Wicki 2023 [70]	CH	CO	5,084,838	52% F / ≥15 y	1	1-3	1	Lden	1, 5
Wicki 2025 [36]	CH	CS	527	51% M / 20-89 y	1	1-3	1	Lden	2, 3
Wu 2024 [66]	US	CS	9,683 – 11,053	62% F / ≥ 20 y	1	5	5	exposure (Y/N), duration	12
Wu 2024 [58]	SE	CO	2,594	61% F / 72 y	1	1-3	1	Lden (1 yr) with 5 yr periods interpolated to 1yr	6
Yang 2023 [39]	UK	CO	424,767	63% M / 40-69 y	1	1	1	Lden, Lnight	2
Ye 2024 [28]	CN	CS	316	100% F / 31 y	3	5	2	LAeq2hr	2, 3, 8
Yu 2024 [95]	CN	CS	480	50-76% M / ≥ 18 y	1	1	1	LAeq24hr	3
Zhang 2024 [29]	CN	CS	6,981	100% F / 15-50 y	1	5	2	LAeq8hr, exposure duration	2
Zhang 2024 [96]	CN	CS	487	54% M / 65 y	2	1,9	2	LAeq15min [‖]	2, 3, 5, 10

Author	Country	Design	Population Characteristics			Noise source(s)	Exposure method(s)	Exposure metric(s) (Time window(s))	Endpoint(s)
			N	Sex / Age (mean, min, or range)	Pop group(s)				
Zhang 2024 [63]	DK	CO	23,141	100% F / ≥44 y	1,3	1	1	Lden, Lday, Leve, Lnight (3 yr)	10
Zhang 2024 [97]	US	CO	194,966	100% F / 62 y (NHS), 46 y (NHSII)	1,3	6	1	L50night	3
Zhang 2025 [64]	CN	CS	2,483	56.6% F / ≥ 60 y	1	6	1	Unclear	4
Zheng 2024 [49]	CN	CS	2,171	56% M / ≥60 y	1	6	5	Unclear	5
Zhou 2025 [98]	CN	CS	306	58% M / 54 y	2	5	2	LAeq15min ‖	3, 5, 11

hr, hour; min, minute; n/a, not applicable; n/r, not reported.

N: * Analysis conducted as part of replication study

Countries: BG = Bulgaria; CA = Canada; CH = Switzerland; CN = China; CZ = Czechia; DE = Germany; DK = Denmark; EE = Estonia; EG = Egypt; ES = Spain; ET = Ethiopia; FI = Finland; FR = France; GR = Greece; HK = Hong Kong; IN = India; IR = Iran; IS = Iceland; IT = Italy; JP = Japan; NL = Netherlands; NO = Norway; SE = Sweden; TW = Taiwan; UK = United Kingdom; US = USA; ZA = South Africa.

Design: CCO = Case crossover; CO = Cohort; CS = Cross-sectional; ECO = Ecological; MA = Meta-analysis; RM = Repeated Measures; TS = Time series; QE = Quasi-experimental.

Pop group(s): 1 = general; 2 = patient; 3 = occupational.

Noise source(s): 1 = Road traffic; 2 = Aircraft; 3 = Railway; 4 = Transportation; 5 = Occupational; 6 = Community/Environmental; 7 = Industrial; 8 = Wind Turbines; 9 = Hospital

Exposure method(s): 1 = modelled; 2 = measured; 3 = recorded playback; 4 = job-exposure matrix; 5 = self-report/perceived

Exposure metric(s) (Time window(s)): Exposure window assumed to be annual for 1 time point (e.g. Lden from 2011 model/map), unless otherwise specified.
† Exposure method validated; ‡ Annual estimates taken every five years; ‖ Estimates taken at more than one time point

Endpoint(s):
1 = Mortality (cause-specific, natural-cause);
2 = Cardiovascular system (stroke, ischemic heart disease, angina, myocardial infarction, atrial fibrillation, heart failure, intracerebral haemorrhage, (pre)hypertension, systolic and/or diastolic blood pressure, ECG abnormalities, mean arterial pressure, blood glucose, haemoglobin, serum B-type natiuretic peptide);
3 = Endocrine system (BMI, waist circumference, overweight, obesity, %body fat, visceral fat, hepatic fat, metabolic score, diabetes, maternal hypertension, gestational diabetes, pre-eclampsia, lipid metabolism, body shape index, distal sensorimotor polyneuropathy, fasting blood glucose, cholesterol, serum sodium, serum potassium, glycaemic indicators: HbA1c, FPG, 2hPG, GSP);
4 = Cancer (colon cancer, thyroid nodules);
5 = Mental health (depression, anxiety, mental health status, postpartum depression, emergency hospitalisations, self-report mental health or anxiety scale, schizophrenia spectrum disorder, bipolar, personality disorders, substance use disorders, suicide);
6 = Neurodegenerative diseases (dementia, cognitive impairment, cognitive impairment/no dementia, global cognitive score, brain MRI markers);
7 = Neurodevelopment;
8 = Perinatal and birth outcomes (foetal size);
9 = Immune response (endothelial function, systemic inflammation response index);
10 = Respiratory system (acute lower respiratory infections, respiratory rate);
11 = Renal function (Renal function indicators: BUN, UAER, SCr, 24hUP);
12 = Musculoskeletal system (rheumatoid arthritis, osteoarthritis);
13 = Well-being in general/patient populations (well-being, self-rated health, headache, stress, hedonic tone)

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Appendix 1: Pubmed search following Engelmann 2024 report

	PECOS criteria	Description	Query
1	Population	General population /adults	humans[MeSH Terms] OR adult[tiab] OR adults[tiab] OR adult[MeSH Terms] OR aged[tiab] OR aged[MeSH Terms] OR man[tiab] OR men[tiab] OR woman[tiab] OR women[tiab]
2	Population	Infants / children / adolescents	Child[tiab] OR children[tiab] OR Adolescent[tiab] OR adolescents[tiab] OR Infant[tiab] OR infants[tiab] OR toddler[tiab] OR toddlers[tiab] OR newborn[tiab] OR baby[tiab] OR babies[tiab] OR boy[tiab] OR boys[tiab] OR girl[tiab] OR girls[tiab] OR postnatal* [tiab] OR post-natal [tiab] OR school* [tiab] OR pediatric* [tiab] OR paediatric* [tiab] OR prenatal[tiab] OR preterm[tiab] OR birth[tiab] OR gestational[tiab] OR pregnancy[tiab] OR fetal[tiab] OR parturition[MeSH Terms] OR Adolescent[MeSH Terms] OR Birth Cohort[MeSH Terms] OR Child[MeSH Terms] OR Infant[MeSH Terms]
3	Population	Unborn children	foetus[tiab] OR fetus[tiab] OR embryo[tiab] OR unborn[tiab] OR pregnan*[tiab]
4	Exposure	Noise	"Noise, Transportation"[Mesh terms] OR (noise[tiab] AND traffic[tiab]) OR (noise[tiab] AND transportation[tiab]) OR (noise[tiab] AND road[tiab]) OR (noise[tiab] AND (airplane[tiab] OR aircraft[tiab])) OR (noise[tiab] AND rail*[tiab]) OR (noise[tiab] AND environmental[tiab]) OR (noise[tiab] AND community[tiab]) OR (noise[tiab] AND wind*[tiab])OR "Noise, Occupational"[Mesh terms] OR (industry[MeSH Terms] AND noise[tiab]) OR (industrial[tiab] AND noise[tiab])
5	Outcome	All-cause mortality	Mortality[tiab] OR death[tiab]
6	Outcome	Cardiovascular diseases	"Vascular Diseases"[Mesh Terms] OR "blood pressure"[Mesh Terms] OR "heart rate"[Mesh Terms] OR "vascular Diseases"[tiab] OR "blood pressure"[tiab] OR "heart rate"[tiab] OR pulse[tiab] OR hypertension[tiab] OR hypertension[Mesh Terms] OR "ischemic heart disease"[tiab] OR "ischemia"[Mesh Terms] OR stroke[tiab] OR stroke[Mesh Terms] OR CVD[tiab] OR "Heart Failure"[Mesh Terms] OR "heart failure"[tiab] OR "Myocardial Infarction"[Mesh Terms] OR "myocardial infarction"[tiab] OR "Coronary Disease"[Mesh Terms] OR "coronary disease"[tiab] OR "Arrhythmias, Cardiac"[Mesh] OR Arrhythmia[tiab]
7	Outcome	Mental health problems	Depression[Mesh Terms] OR depress*[tiab] OR "Depressive Disorder"[Mesh Terms] OR "Mental Health"[Mesh Terms] OR "Mental Disorders"[Mesh Terms] OR "mental health"[tiab] OR anxiety[MeSH Terms] OR anxiety[tiab] OR suicide[MeSH Terms] OR suicide[tiab]

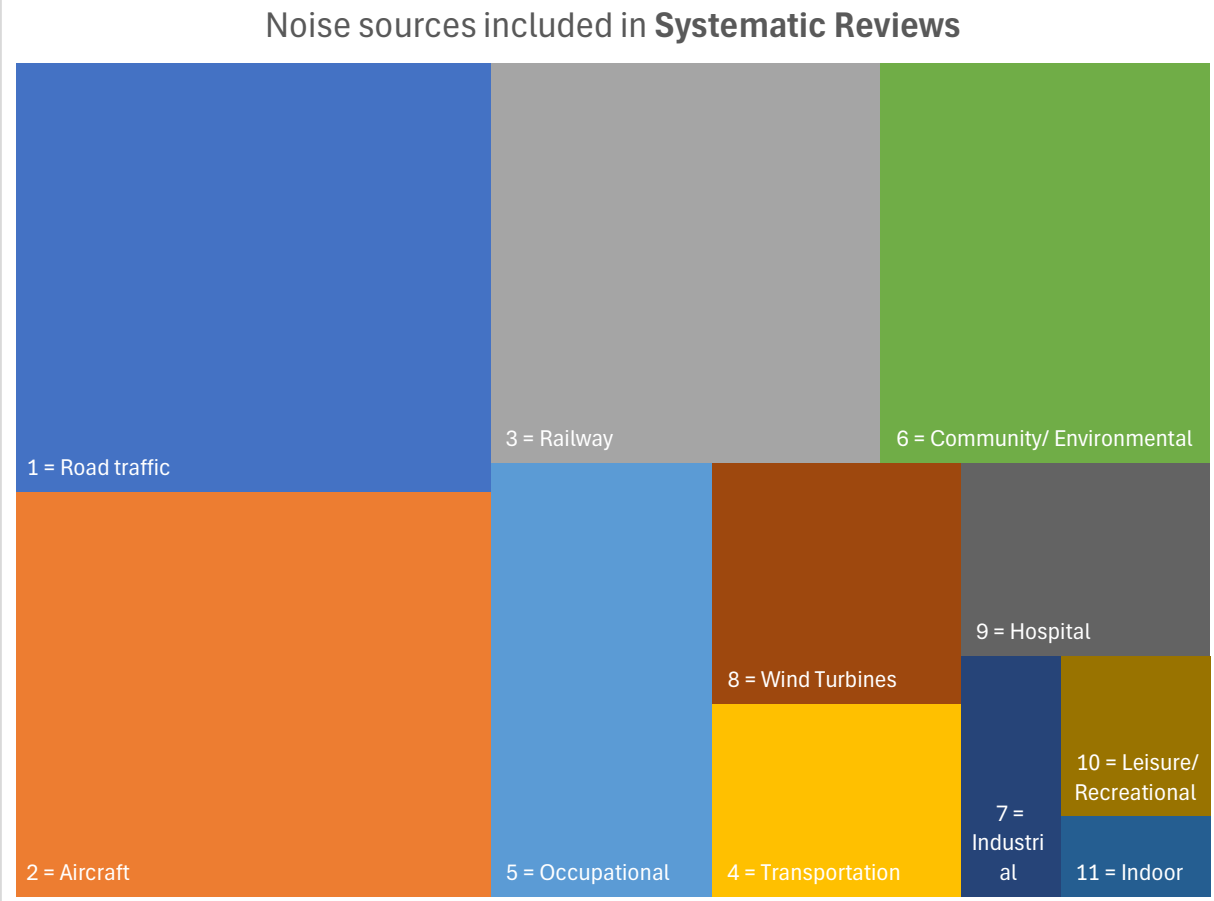
8	Outcome	Diabetes	"diabetes mellitus"[MeSH Terms] OR diabetes[tiab] OR "diabetes, gestational"[MeSH Terms] OR "gestational diabetes"[tiab]
9	Outcome	Cognitive impairment	"cognitive dysfunction"[MeSH Terms] OR "cognitive decline"[tiab]
10	Outcome	Dementia	Dementia[Mesh] OR "Alzheimer Disease"[Mesh] OR Dement*[tiab] OR "Alzheimer Disease"[tiab]
12	Outcome	Overweight	Overweight[Mesh Terms] OR overweight[tiab] OR BMI[tiab] OR "body mass index"[tiab] OR "waist circumference"[tiab] OR "body mass index"[Mesh Terms] OR "waist circumference"[Mesh Terms]
13	Outcome	Respiratory	"respiratory tract diseases"[MeSH Terms] OR "respiration disorders"[MeSH Terms] OR respiratory [tiab]
14	Outcome	Cancer	"neoplasms"[MeSH Terms] OR cancer[tiab]
15	Study type	Reviews	"Systematic review"[tiab] OR metaanalysis[tiab] OR "meta analysis"[tiab] OR "systematic review"[Publication Type] OR "meta analysis"[Publication Type] OR "Meta-Analysis as Topic"[MeSH Terms] OR review[tiab] OR Review [Publication Type]
16	Study type	Original studies	"Cohort Studies"[Mesh Terms] OR cohort[tiab] OR "case-control studies"[MeSH Terms] OR case control [tiab] OR case-control [tiab] OR case[tiab] AND ("cross-over studies"[MeSH Terms] OR crossover [tiab]) OR intervention [tiab]"Cross-Sectional Studies"[Mesh] OR cross-sectional[tiab] OR ecological[tiab]
	Search period[a]		(from 2023/1/1 - 2025/12/31)

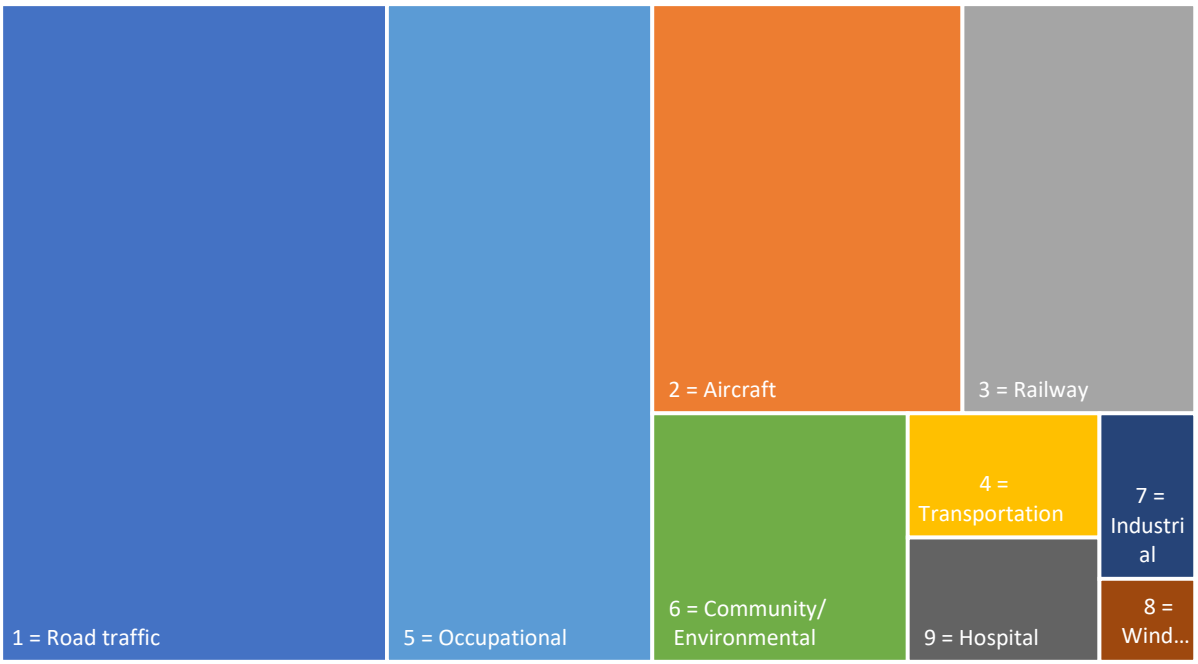
[a] JJJJ/MM/DD = date of search

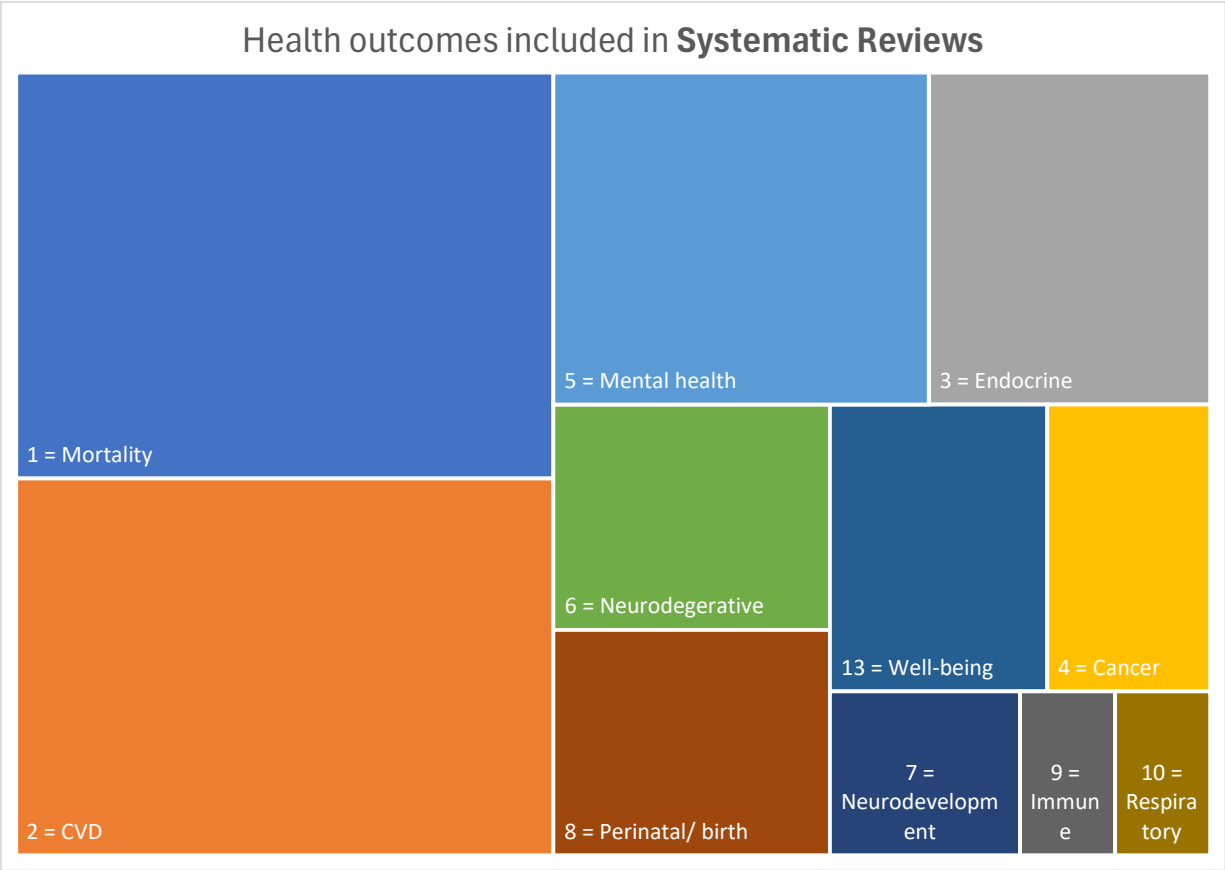
Search terms within each search grid category were expanded with “OR” and the different categories combined with “AND”.

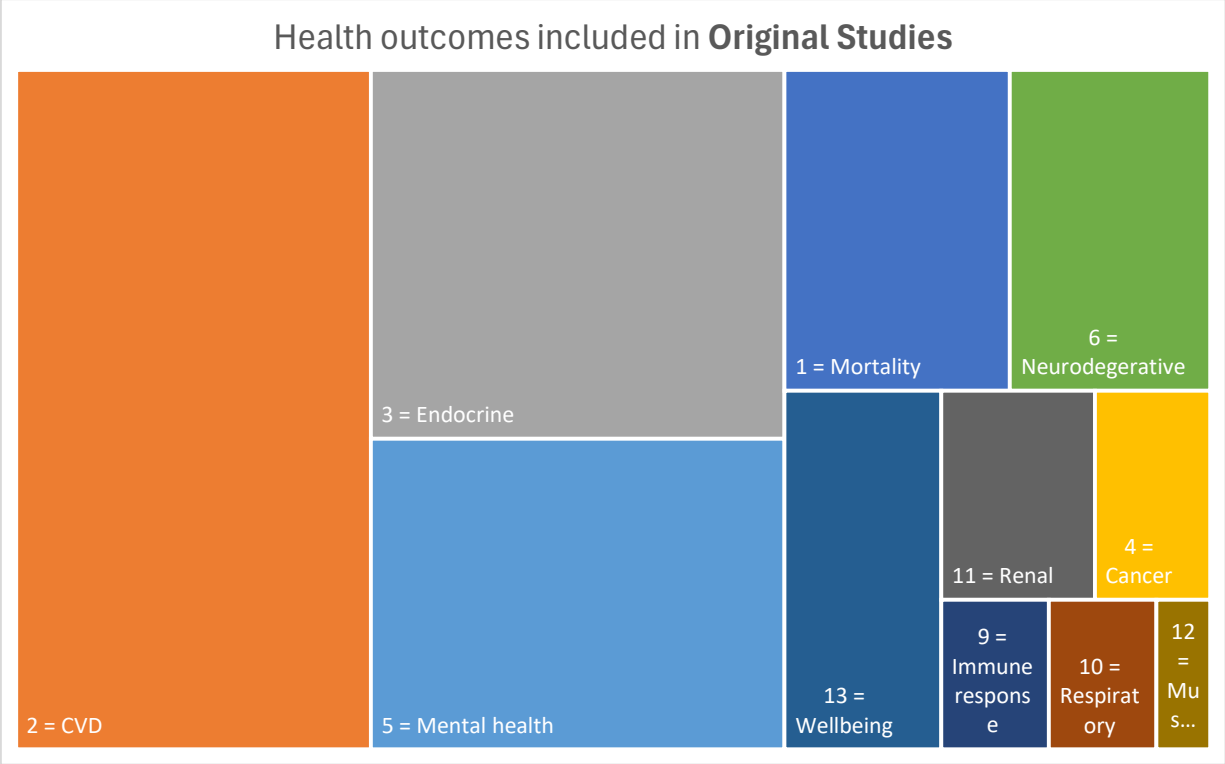
(#1 OR #2 OR #3) AND #4 AND (#5 OR #6 OR #7 OR #8 OR #9 OR #10 OR #11 OR #12 OR #13) AND (#14 OR #15) plus date filter

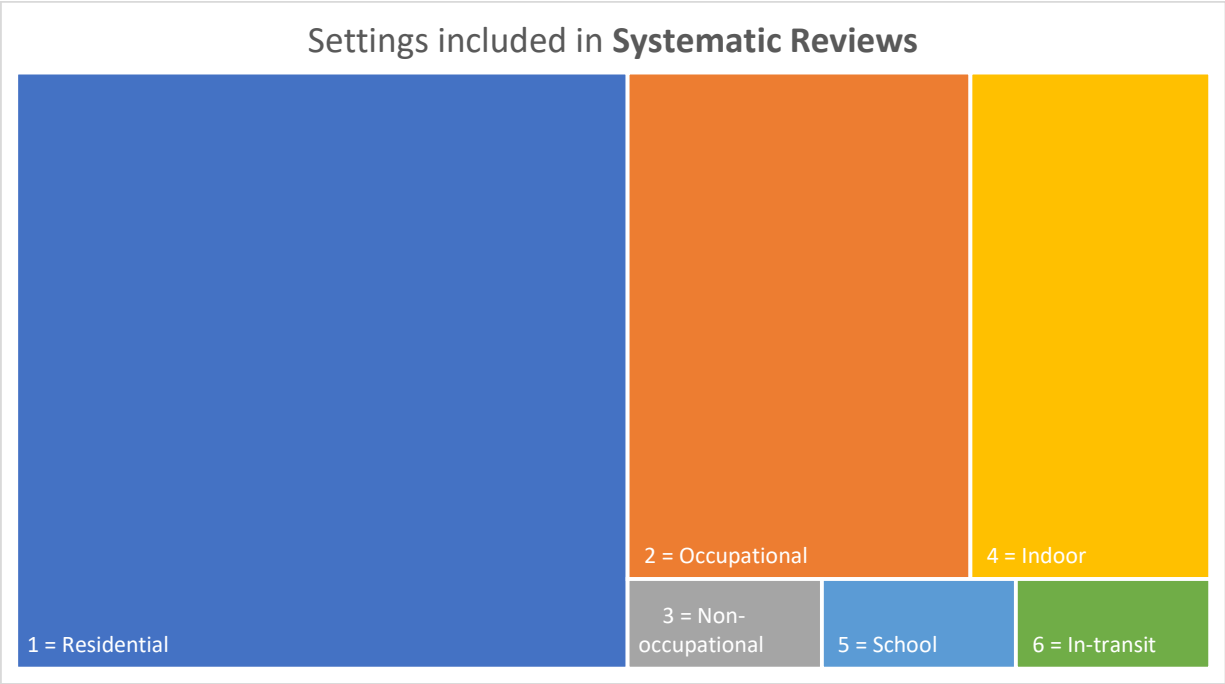
Appendix 2: Visual overview of the literature included in the review (systematic reviews and original studies)
Numbers in Treemaps correspond to footnotes in Table 1 and 2

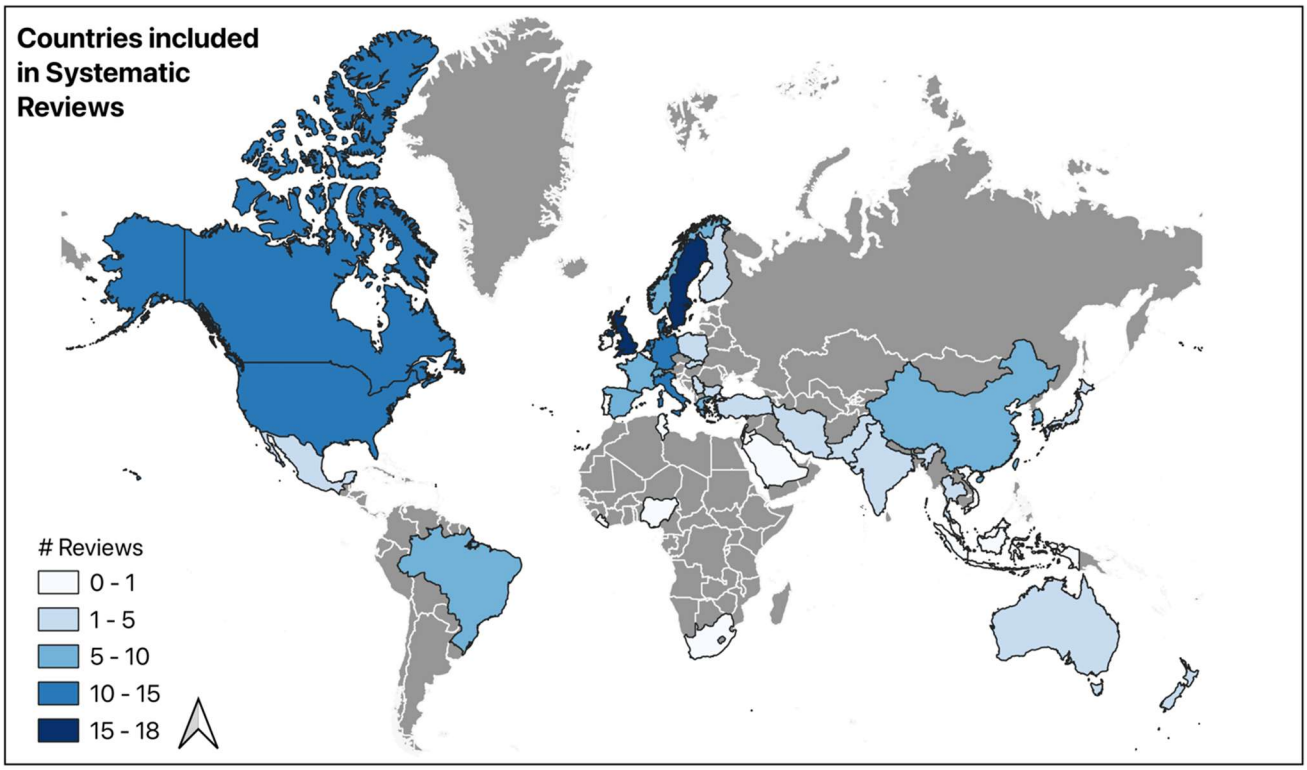





Health outcomes included in **Systematic Reviews**
1 = Mortality
5 = Mental health
3 = Endocrine
2 = CVD
6 = Neurodegerative
13 = Well-being
4 = Cancer
8 = Perinatal/ birth
7 = Neurodevelopment
9 = Immune
10 = Respiratory

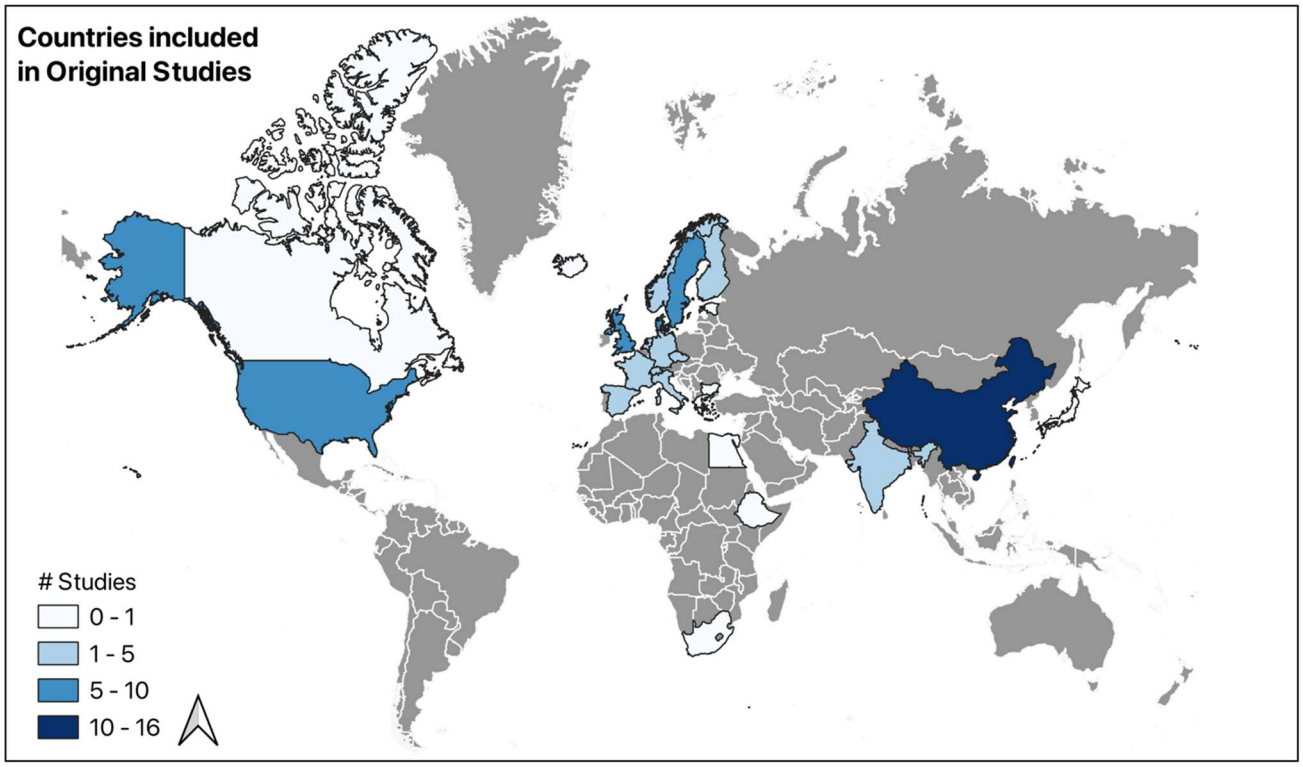

Health outcomes included in **Original Studies**
3 = Endocrine
1 = Mortality
6 = Neurodegerative
2 = CVD
5 = Mental health
13 = Wellbeing
11 = Renal
4 = Cancer
9 = Immune response
10 = Respiratory
12 = Mus...


Settings included in **Systematic Reviews**
1 = Residential
2 = Occupational
4 = Indoor
3 = Non-occupational
5 = School
6 = In-transit



Notes for Systematic Reviews map:

- Some countries may be overestimated due to reviews that included other exposures.
- Several reviews only cited region which are not reflected in the map (n= 2 North America, n=1 Asia).



Appendix 3: Narrative and bibliometric reviews

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Noise as a Public Health Problem

Trait or State? Challenging the Stability of Noise Sensitivity (WNS-6B)

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ABSTRACT

Noise sensitivity is a crucial moderator in noise annoyance models, traditionally regarded as a stable personality trait. This research challenges this axiom by investigating the temporal variability of noise sensitivity. Using a weekly Technical Listening Training (TLT) program as a high-frequency sampling environment over two years (N = 72), we monitored WNS-6B scores. Statistical analysis revealed that the majority of participants exhibit significant intraindividual fluctuations. These findings suggest that noise sensitivity possesses strong statelike characteristics, fluctuating in response to situational factors, which carries profound implications for the validity of single-point environmental noise assessments.

INTRODUCTION

Noise sensitivity has long been conceptualized as a stable, personality-like trait that governs an individual's psychological and physiological reactivity to sound [1, 2]. As a critical moderator in the dose-response relationship, Noise sensitivity has been shown to be a more potent predictor of individual noise annoyance than objective physical parameters [3, 4]. Conventional models often treat this sensitivity as a "static filter," assuming that an individual's vulnerability remains relatively constant throughout their adult life, a view supported by research on both genetic predispositions [5] and long-term environmental exposure impacts [6, 7]. However, this traditional "Trait" paradigm has recently been challenged by the need for a more dynamic understanding of environmental perception. Growing evidence suggests that auditory perception is not a fixed mechanism but a plastic process that may oscillate under the influence of fluctuating internal states—such as psychological stress, mental health conditions, and overall health-related quality of life [8, 9, 10]. Despite these theoretical developments, the assumption of temporal stability in Noise sensitivity remains a cornerstone of current urban noise policies and public health guidelines [11]. If Noise sensitivity indeed exhibits short-term fluctuations, a single assessment point may fail to accurately capture an individual's true susceptibility at any given time [6, 7].

The primary obstacle to resolving the "Trait vs. State" debate has been the lack of high-frequency, longitudinal data. In this research, we address this gap by utilizing a "Technical Listening Training" (TLT) program as a high-frequency sampling environment [12]. TLT is an

intensive curriculum designed to refine auditory discrimination skills through rigorous weekly sessions [12]. While previous research by the authors utilized TLT to examine the relationship between auditory task performance and noise sensitivity [12], the temporal stability of the sensitivity scores themselves across multiple sessions has not been fully scrutinized.

Over a two-year period beginning in 2022, we tracked the noise sensitivity of university students using the Weinstein's Noise Sensitivity scale (WNS-6B) administered at the start of every session [8, 12]. By analyzing the fluctuations in these weekly scores, we examine whether individuals can be categorized into stable (Stable-High/Low) or unstable sensitivity groups [12]. Our core research question focuses on whether Noise sensitivity remains stable over time or exhibits "state-like" fluctuations driven by situational factors. This study investigates the magnitude of these fluctuations and explores their relationship with students' auditory task performance [12]. By documenting these temporal shifts, this paper seeks to provide an essential first step toward a more nuanced, dynamic model of noise sensitivity that acknowledges the interplay between stable traits and transient states.

METHODS

Experimental Field: Technical Listening Training (TLT) Program

Media Basic Unit II, a compulsory seminar for sophomore students in the Department of Information Media at Kanagawa Institute of Technology. The primary objective of this course is Technical Listening Training (TLT), a systematic educational method designed to enhance auditory discrimination capabilities [12]. The training utilizes the "Shinji-online" system, a cloud-based pedagogical platform. This system facilitates various auditory tasks, including the discrimination of sound pressure levels (in 1.0 dB increments), frequency components (octave-band filtering), and temporal characteristics of sound. Each session took place in a controlled computer laboratory environment. Sound stimuli were delivered through high-fidelity audio interfaces and calibrated loudspeakers (or headphones, depending on the task) to ensure objective consistency in acoustic exposure across participants. The total duration of each session was 90 minutes. A critical methodological feature of this study was the sequence of assessments: the psychological questionnaires were strictly administered during the first 10 minutes of each session, as shown in Figure 1. This timing ensured that the participants' reported noise sensitivity was not influenced by the fatigue or emotional response generated by the intensive auditory tasks of that day.

Participants and Temporal Design

The study followed a longitudinal cohort design spanning two academic years: fiscal year (FY) 2022 (n = 35) and FY2023 (n = 37), involving a total of 72 participants. All participants were approximately 19 – 20 years old. The longitudinal data collection continued for 13 - 14 consecutive weeks per year, mirroring the academic semester schedule. By sampling at a weekly frequency, the study aimed to bridge the gap between momentary ecological assessments and long-term personality surveys, thereby capturing the meso-scale temporal dynamics of noise sensitivity.

Instrumentation: WNS-6B Scale and Binary Transformation

To assess noise sensitivity, we employed the Japanese version of the Weinstein's Noise Sensitivity scale, abbreviated to its 6-item version (WNS-6B) [8, 12]. The items cover various dimensions of noise reaction, such as physical reactivity, emotional attitude, and self-identification. Originally, participants rated these items on a 6-point Likert scale. To eliminate non-linearities in subjective scaling, we converted the responses into a binary scale (0 or 1). Ratings reflecting any degree of agreement (points 4, 5, and 6) were coded as 1, while disagreement (points 1, 2, and 3) were coded as 0 [8]. The total NS score per session was

calculated as the sum of these binary items (Range: 0–6). This transformation logic is visualized in Figure 2.

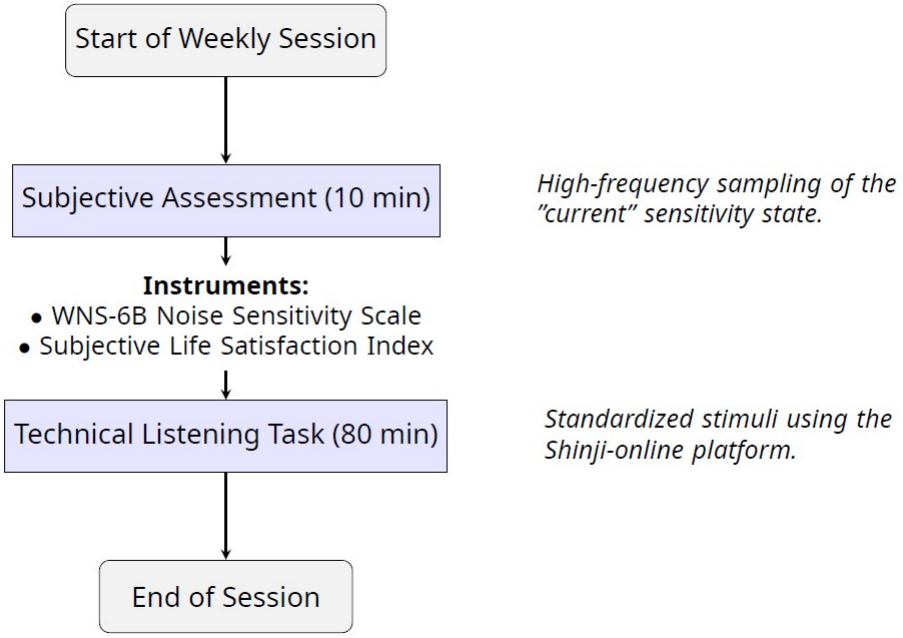

Figure 1: Longitudinal sampling protocol. Arrows now follow the logical flow of information to ensure clarity in the integration of subjective and objective tasks.

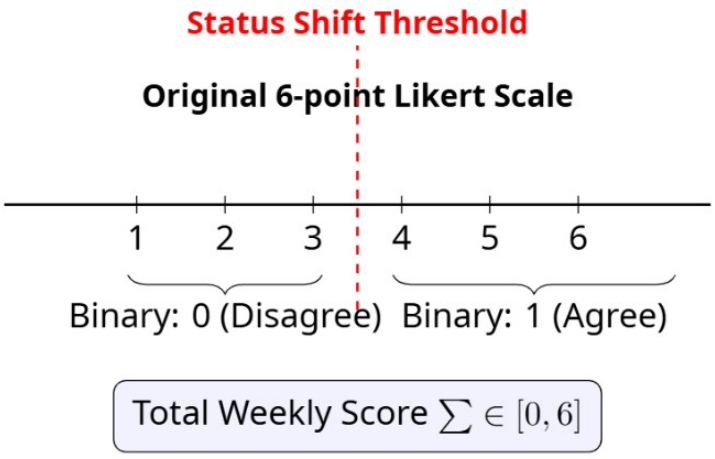

Figure 2: Binary scoring methodology designed to robustly capture the categorical fluctuation of sensitivity states.

Categorization Logic for Sensitivity Stability

A primary focus of our methodology was the identification of individuals who do not conform to the "stable trait" model. Using the group median as a categorical threshold for each session, participants were assigned to one of three groups based on their behavior over 14 weeks [12]:
• **Stable-High:** Participants whose total WNS-6B score consistently resided in the high-sensitivity half across all weeks.

• **Stable-Low:** Participants who consistently remained in the low-sensitivity half.
• **Unstable:** Participants who exhibited dynamic fluctuations, crossing the group median threshold at least once during the semester.

Synchronization with Performance Indices

The Shinji-online system automatically records a Total Rate index. To synchronize these performance metrics with the weekly psychological data, we aggregated the sessions into five Training Numbers (Table 1).

Table 1: Synchronization map between weekly survey sessions and performance aggregation windows.

Training Number	Aggregate Sessions (FY2022)	Aggregate Sessions (FY2023)
1 (First)	Weeks 1–2	Weeks 1–3
2	Weeks 3–5	Weeks 4–6
3 (Middle)	Weeks 6–9	Weeks 7–10
4	Weeks 10–11	Weeks 11–12
5 (Last)	Weeks 12–13	Weeks 13–14

METHODS

Temporal Stability of Group Averages vs. Individual Fluctuations

Statistical analysis of the longitudinal data indicates a dual nature of noise sensitivity. As shown in Table 2, the group-average WNS-6B score remained relatively stable across the semester in both years, with a significant temporary decrease observed only during the mid-semester of FY2022 ($p < 0:05$). This apparent stability at the group level, however, masks profound intraindividual variability.

Table 2: Temporal changes in average WNS-6B scores and training performance [12].

Metric	FY2022 ($n = 35$)			FY2023 ($n = 37$)		
	First	Middle	Last	First	Middle	Last
WNS-6B score average	3.4	2.6*	3.4	3.2	3.1	3.2
Training Score (TotalRate)	799.5	944.6*	914.3	998.7	928.0*	985.2

*Significant difference compared to the 'First' timing ($p < 0.05$).

Figure 3 shows the raw WNS-6B score trajectories for representative individuals over 14 weeks. While some participants maintain stable scores, the majority exhibited oscillating behavior, crossing the population median multiple times. This confirms that for a significant portion of the population, noise sensitivity is a dynamic state.

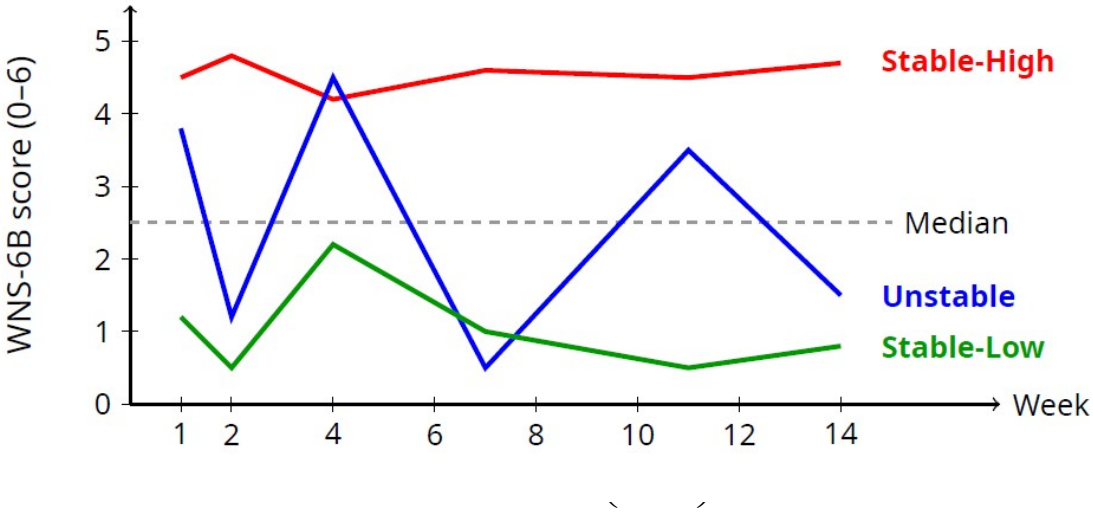

Figure 3: Temporal trajectories of WNS-6B scores for representative participants

Quantifying the ”State” Component

To statistically validate the state-dependent nature of noise sensitivity, we decomposed the variance and analyzed the distribution of intra-individual temporal standard deviations ($SD_{temporal}$). As shown in Figure 4, approximately 60% of participants exhibited an SD > 1:0, reinforcing the finding that sensitivity levels are subject to oscillations.

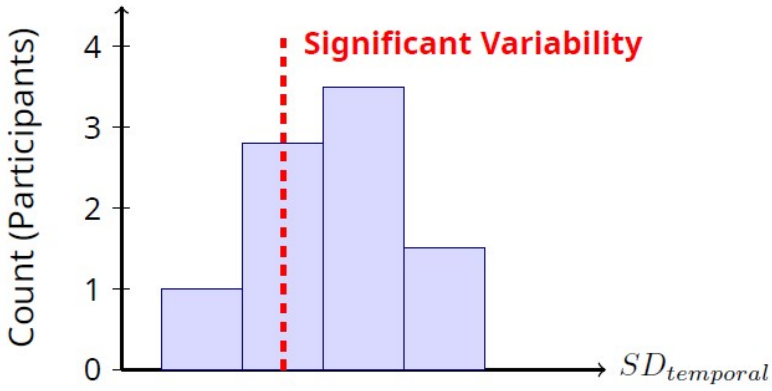

Figure 4: Distribution of intra-individual temporal variability in WNS-6B scores.

DISCUSSION: THE PARADIGM SHIFT FROM TRAIT TO STATE

The Vulnerability Paradox

A core contribution of this research is the identification of the Vulnerability Paradox. Traditional models assume that noise-sensitive individuals are consistently reactive. However, our data suggest that high noise sensitivity is linked to high temporal volatility. This implies that sensitivity should be re-defined not merely as a threshold, but as a high reactivity to transient states.

Implications for Noise Policy

The presence of a majority Unstable group call for a fundamental re-evaluation of how noise sensitivity is measured. Single-shot surveys used in urban planning may misrepresent the long-term risk for more than half of the population. We propose a Dynamic Assessment model (Figure 5).

Figure 5: Conceptual decomposition of noise sensitivity into stable trait and dynamic state components.

CONCLUSION

This study experimentally verified that noise sensitivity is not an immutable trait but exhibits significant state-like fluctuations over short temporal intervals. Through high-frequency longitudinal sampling within an auditory training environment, we have demonstrated that intraindividual variability is a dominant feature for the majority of the population.Our findings lead to several critical conclusions:

1. **Categorical Instability:** Between 51% and 74% of participants exhibit ”Un stable” noise sensitivity, frequently shifting across the population median. This suggests that a single point measurement of noise sensitivity (the ”snapshot” approach) is insufficient for capturing an individual’s true susceptibility to sound.
2. **Interaction with Performance:** The ”Stable-Low” group demonstrated unique learning trajectories in technical listening tasks. Conversely, the ”Unstable” group showed patterns similar to the ”Stable-High” group, suggesting that even transient states of high sensitivity may moderate auditory skill acquisition or induce cognitive fatigue.
3. **The Vulnerability Paradox:** Individuals with higher average noise sensitivity also exhibit the greatest temporal volatility. This finding provides a statistical foundation for a dynamic model where high sensitivity is synonymous with high state-reactivity. These results have profound implications for environmental noise management and urban planning. Current guidelines, which often treat sensitivity as a fixed moderator, may fail to protect individuals during their most vulnerable ”states.” Future research will integrate life satisfaction and physiological stress markers to identify the specific drivers of these shifts, aiming to develop more personalized and dynamic noise protection strategies.

The next phase of this research will involve a rigorous statistical analysis to quantify the complex interplay between psychological well-being and noise sensitivity shifts. By identifying the specific psychological predictors and physiological drivers, we aim to establish a more robust, multi-dimensional model for environmental noise assessment. The comprehensive results of these ongoing longitudinal surveys and their implications for personalized noise protection strategies will be reported in forthcoming publications.

Acknowledgements

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Teachers' satisfaction, wellbeing, noise exposure, and co-teaching in enclosed and flexible learning spaces

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ABSTRACT

Modern schools include traditional enclosed classrooms for 20–30 students and flexible or open areas for several groups. Our previous work showed that room-acoustic solutions in open learning spaces complied less with Finnish acoustic regulations than those in enclosed rooms, but activity sound levels were slightly lower in open (63 dB L_{Aeq}) than in enclosed spaces (65 dB L_{Aeq}). Teachers were more dissatisfied with flexible spaces and a larger share of them reported that the environment did not support their preferred teaching methods. This raised the question of whether flexible spaces were used as intended, and whether a mismatch between space and pedagogy contributes to wellbeing. This study examines whether teachers' wellbeing and satisfaction with their working environment are influenced by the learning space type (flexible vs traditional enclosed), the use of co-teaching, and the interaction between space type and co-teaching. Here 319 teachers' answers were further examined (237 in enclosed group and 80 in flexible group). The flexible group was less satisfied with their workspace, especially with sound environment, disturbances, and sound insulation to neighboring groups than the enclosed group. These differences, however, were not reflected in wellbeing, such as job satisfaction, ability to work, or need for recovery. The use of co-teaching was related to lower need for recovery than no co-teaching. The interaction of learning space type and co-teaching was not significant with any wellbeing variable. The study suggests that besides the space type the use of space should be examined in more detail in the future.

INTRODUCTION

Modern schools have many different types of learning spaces. Traditional classrooms typically accommodate a single group of 20–30 students while flexible learning environments allow multiple groups to share a larger, open area, sometimes separated by movable walls or left

completely open. How these different learning spaces influence the usage, wellbeing and sound environment of people working there has not been addressed completely.

Our previous findings showed that the room acoustic solutions in open learning spaces were less in accordance with Finnish acoustic regulations than in enclosed learning spaces [1]. In these same schools, the teaching staff were also more dissatisfied with flexible learning spaces than with enclosed learning spaces, both in general and with their sound environment [2]. However, when we measured the activity sound in these schools, the sound levels during teaching were slightly lower in open than in enclosed learning spaces [2].

In our study, the difference between flexible and enclosed learning spaces was small: 63 dB L_{Aeq} in flexible and 65 dB L_{Aeq} in enclosed learning spaces [2]. This was surprising, as previous research has shown that noise from adjacent groups can increase the sound levels by as much as 10 dB L_{Aeq} if the activity in the neighbouring space is loud [3]. The small difference in our measurements does not suggest different health effects between learning spaces. This small difference, in an unexpected direction, was hypothesized to be due to differences in the type of activity, the openness of the learning spaces, or simply a random result [2].

Subjective assessments, however, indicated that teaching staff working in flexible learning spaces were more dissatisfied with the sound environment, the amount of space, and disturbances than those working in enclosed learning spaces [2]. We aimed to further investigate whether these disturbances and general dissatisfaction with the learning environment could be linked to adverse health effects, such as a greater need for recovery.

Not only sound levels, but also other factors as the use of space, might influence the relationship between space and wellbeing. Flexible learning spaces are intended to support a wider variety of teaching methods and student-centered pedagogies, which enclosed classrooms may limit [4]. To our surprise, our previous findings showed that a larger proportion of teaching staff in flexible spaces reported that the space does not support the teaching activities they would like to use (29% in flexible spaces and 15% in enclosed spaces) [2]. This was contrary to our expectations, as flexible spaces are claimed to better support, for example, co-teaching due to possibility of flexible group sizes and varied use of space. This raised a question of whether flexible spaces are used in the intended way. Flexible learning spaces could be better suited for co-teaching than enclosed learning spaces, which might be reflected in the experience and wellbeing of teachers. Therefore, not only the space type, but also the interaction between space type and its usage should be examined.

This study examines whether teachers' wellbeing and satisfaction with their working environment are influenced by the type of learning space and how they use it.

The research questions were

1. Do teachers in flexible and traditional learning spaces differ in their self-reported wellbeing?
2. Do teachers using co-teaching differ in their self-reported wellbeing from teachers not using co-teaching?
3. Is there an interaction between learning space type and co-teaching in teachers' self-reported wellbeing?

METHODS

Schools

The study examined 21 primary schools in Southern Finland. They were selected so that 10 presented schools with mostly traditional enclosed classroom layout, while 11 schools had several flexible or open learning spaces. All schools were either new or renovated recently and they did not have any special indoor air quality problems. All teaching staff working in these schools in the learning spaces with students were invited to answer a questionnaire. In addition, all learning spaces were visited, and the principals were interviewed about the usage of school.

Furthermore, four learning spaces in each of the 20 study schools were studied in more detail: room acoustic measurements were performed [1], and their activity sound pressure levels were measured over five working days [2]. These learning spaces were used by students in grades 3 to 6.

The Human Sciences Research Ethics Committee of Turku University of Applied Sciences approved the study (LP09_2022, 3.10.2022). The approval for the study was applied also from the municipalities or towns organizing teaching as well as from the schools participating in the study.

Participants

All teaching staff working in learning spaces of these study schools were invited to answer the questionnaire. 361 members of teaching staff answered the questionnaire. Here we analyzed only the 319 teachers that answered. Majority of them were women (82%). See more details in [2].

Questionnaire answers

The participants were divided into two **learning space** groups according to the type of the learning space they mostly used inquired with a question: "What is the most common space you use for teaching?" The response options were: A) A space where one class/group and one teacher operate simultaneously, B) A space where multiple classes/groups and teachers operate simultaneously, C) A flexible teaching space (a closed teaching space, plus, for example, an aquarium outside the space, or a corridor/common area to which the teaching space can be expanded), D) Other, what kind? Respondents in category A were classified into the enclosed space group, while all other respondents were classified into the flexible space group.

Teaching style was defined using the question: “Do you use co-teaching in your teaching?” The response options were: Usually, Often, Rarely, Never, and Does not concern me. Respondents answering “Usually” or “Often” were classified as using co-teaching activities in their teaching (co-teaching), and all other options were coded as involving few or no co-teaching activities (no co-teaching).

Environmental satisfaction was assessed with several questions using similar scales. Satisfaction related to the quality of sound environment was asked with the question: “How satisfied are you with the following factors in your learning space?” The factors examined here are the sound environment, the undisturbedness of space, and the sound insulation to neighbouring group (see a more detailed description of all indoor environmental quality factors in [2]). The response scale ranged from -3 Very dissatisfied, to + 3 Very satisfied. **Workspace satisfaction** was assessed with the following questions: “How satisfied are you with your

learning space in general". The response scale was the same as for environmental satisfaction.

Subjective noise exposure was assessed as self-rated noise exposure in the study [5]. The question was: "Are you exposed to noise that disturbs you when you are teaching in your learning space." The response scale was: 1 – Never; 2 – Very rarely or very little; 3 – Approximately ¼ of the time; 4 – Approximately half of the time; 5 – Approximately ¾ of the time; 6 – Almost all the time. The responses were treated as continuous variable, with higher numbers denoting more often subjective noise exposure.

Health and wellbeing were measured with questions regarding job satisfaction, work ability, and need for recovery. **Job satisfaction** was asked with the question: "How satisfied are you with your work as a whole?" Responses were on a five-point scale: 1 = Very dissatisfied, 2 = Quite dissatisfied, 3 = Neither satisfied nor dissatisfied, 4 = Quite satisfied, 5 = Very satisfied. The question for **work ability** was: "How would you rate your current work ability?" Responses were on a five-point scale: 1 = Very poor, 2 = Poor, 3 = Moderate, 4 = Good, 5 = Very good. **Need for recovery** after the workday was assessed using three items from the Need for Recovery scale [6], with answers summed on a five-point scale; a higher score indicating a greater need for recovery. The final scale for Need for Recovery is between 3-15.

Statistical analysis

The differences in wellbeing were analysed using Generalized Linear Mixed Effects analysis with learning space group and teaching style as the fixed effects and the school as a random effect. The linear mixed effects analysis with lmer function from (4lme package in R) was used and the models were fitted with restricted maximum likelihood (REML) with Satterthwaite's approximations.

RESULTS

80 teachers (25%) reported teaching mainly in flexible spaces, and 237 (75%) reported teaching mainly in enclosed spaces. Most teachers reported using co-teaching usually or often (207 teachers, 65%, co-teaching) while only 110 teachers (35%) reported using co-teaching less often (no co-teaching). Table 1 shows the number of respondents the in learning space groups in relation to teaching style.

Table 1. The numbers of respondents presented for learning space type and teaching style.

	Co-teaching	**No co-teaching**
Enclosed	141	96
Flexible	66	14

Teachers working in flexible spaces were less satisfied with their workspace than those teaching in enclosed spaces (Table 2; Figure 1a). They also reported being less satisfied with their sound environment ($p=.003$), the undisturbedness of space ($p=.002$), as well as the sound insulation to neighbouring groups ($p<.001$) (Table 2; Figures 1b-d). Teaching styles or the interaction between learning space and teaching style did not influence environmental satisfaction ratings ($p>.05$).

Table 2. The relation between learning space group and teaching style and their interaction with teachers' satisfaction with their environment.

Satisfaction with	Learning space	Teaching style	Learning space * Teaching style
Workspace	**F(1, 313) = 6.9, p = .009**	F(1, 310) = 0.1, p = .792	F(1, 310) = 0.1, p = .756
Sound environment	**F(1, 313) = 9.1, p = .003**	F(1, 310) = 0.0, p = .816	F(1, 310) = 0.1, p = .714
Undisturbedness	**F(1, 313) = 9.7, p = .002**	F(1, 310) = 1.6, p = .203	F(1, 310) = 1.1, p = .300
Sound insulation to neighboring groups	**F(1, 313) = 12.5, p < .001**	*F*(1, 309) = 0.2, *p* = .656	*F*(1, 309) = 2.5, *p* = .118

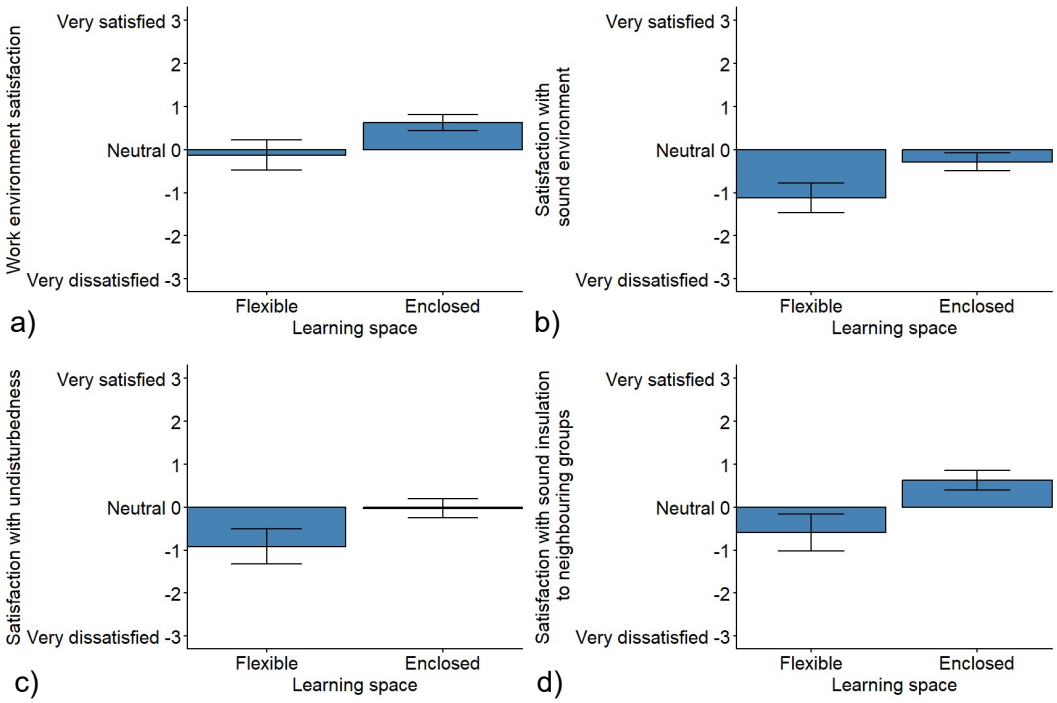

Figure 1. The mean values of teachers' estimations of a) satisfaction with workspace, b) sound environment, c) undisturbedness of the space, and d) sound insulation into neighbouring groups in different learning spaces. Error bars denote 95 % confidence intervals.

Teachers teaching in the flexible spaces reported being more often exposed to disturbing noise than those teaching in enclosed spaces (p=0.009, Table 3, Figure 2a). Learning space groups did not differ from each other in other well being factors, like job satisfaction, work ability, or need for recovery (Table 3). Teaching style groups did not differ in workspace satisfaction, job satisfaction, work ability, subjective noise exposure (p>.05), but they differed in the need for recovery (p=.007) (Table 3). The need for recovery was lower in co-teaching group (mean=10.0) than in no co-teaching group (mean=10.7) (Figure 2b).

No significant interaction between the learning space group and the teaching style were observed in any examined factor (p>0.05) (Table 3).

Table 3. The relation between learning space group and teaching style and their interaction with teachers' wellbeing.

Wellbeing factors	Learning space	Teaching style	Learning space * Teaching style
Subjective noise exposure	**F(1, 308) = 6.8, p = .009.**	F(1, 304) = 1.3, p = .254	F(1, 304) = 3.4, p = .067
Job satisfaction	F(1, 309) = 0.5, p = .468	F(1, 311) = 1.4, p = .233	F(1, 311) = 0.6, p = .457
Work ability	F(1, 302) = 0.9, p = .345	F(1, 312) = 0.6, p = .452	F(1, 313) = 0.7, p = .419
Need for Recovery	F(1, 308) = 3.3, p = .070	**F(1, 312) = 7.3, p = .007**	F(1, 312) = 2.4, p = .126

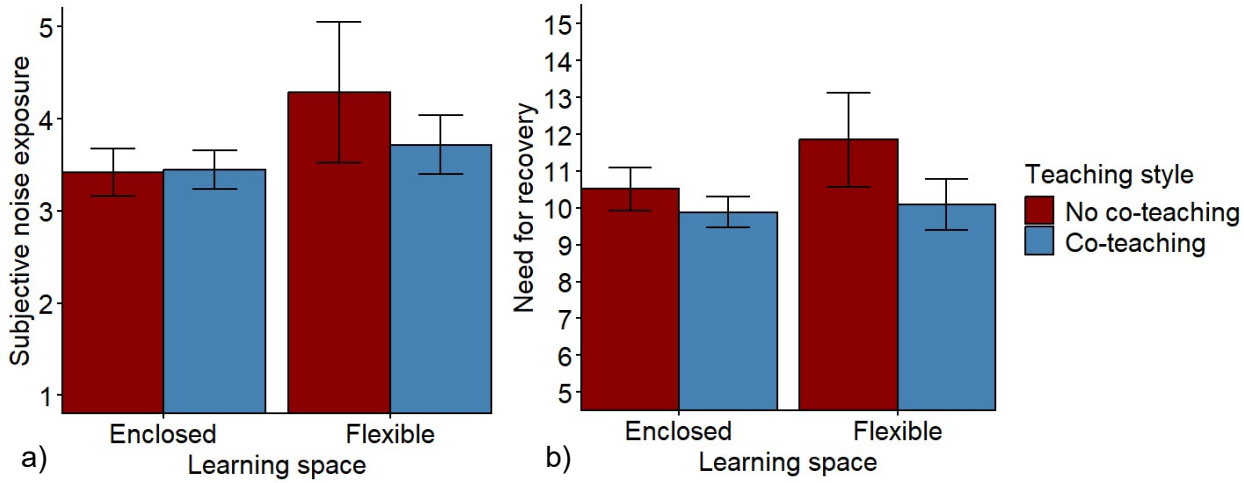

Figure 2 a and b. The means of teachers' estimations of their a) subjective noise exposure and b) need for recovery in relation to learning space groups and teaching styles. Higher values mean higher subjective noise exposure and higher need for recovery. Error bars denote 95 % confidence intervals.

DISCUSSION

Teachers teaching in flexible spaces were less satisfied with their overall work environment than those teaching in enclosed spaces. They reported lower satisfaction with the sound environment, the undisturbedness of space as well as the sound insulation to neighbouring groups. Teaching style did not moderate this relationship. Teachers also reported more frequent exposed to harmful noise in flexible than in enclosed spaces. Previous measurements of activity sound pressure levels, however, indicate that this disturbance is related less to higher activity sound levels [2], and more to room acoustic solutions that do not comply with the new Finnish regulations [1] as well as disturbances from other school activities such as circulation routes and neighbouring groups.

This led us to ask whether the dissatisfaction with the sound environment is related to how teachers use the space. Our data on the influence of teaching style defined by use of co-teaching indicate that this is not the case. Teaching style was not a significant factor in any of the satisfaction ratings examined. The learning space groups did not show differences in wellbeing factors such as job satisfaction, work ability, or need for recovery.

Our next question was whether teaching style, i.e., co-teaching, influenced teachers' wellbeing or whether this interacted with the learning space type. Interestingly, we found that teachers using co-teaching had a lower need for recovery than teachers' not using co-teaching. Having another adult with whom to plan and teach might help reduce teachers' burden, especially in schools with large group sizes. Co-teaching also enables more flexible student groupings.

These results, however, must be interpreted with caution: during our visits to schools and interviews with principals we noticed that many teachers have different understanding of what co-teaching is. Therefore, we think teaching style and space type require further examination.

The lower SPLs in open spaces suggest that the negative experience is not due to loud volume but rather to a lack of cognitive ergonomics. Nevertheless, this negative experience related to workspaces does not appear to be strong enough to directly impair teachers' wellbeing.

Conclusions

The main negative issue in flexible learning spaces is disturbance which causes dissatisfaction among teachers. The type of activity did not influence the satisfaction with the school environment, but the learning space types did. Learning space type was not related to differences in teachers' wellbeing. Co-teaching might help teachers to reduce their strain, but this result requires further verification.

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Perception of Noise Exposure in Industrially Burdened Areas

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ABSTRACT

The present study aimed to assess the use of a standardized questionnaire methodology to evaluate perceptions of industrial noise and health-related risks in two industrially burdened regions. The study included 196 respondents, 59 residing in the vicinity of a surface coal mine in the Turów region (Czech–Polish border area) and 137 near a large petrochemical refinery in Bratislava, Slovakia. Data were collected through a structured questionnaire that assessed demographics, health status, lifestyle, and risk perception of general and environmental stressors, using a five-point Likert scale. Long-term nocturnal noise monitoring was conducted in residential areas adjacent to those affected regions. Acoustic monitoring at Slovnaft revealed noise limit exceedances of up to 10.3 dB during nighttime. Short-term noise exposure limits recorded in the vicinity of the Turów mine were exceeded, but long-term noise limits were not violated. Comparative analysis revealed significant differences in risk perception. While the economic situation of the state was a shared concern, other priorities varied. In the Turów region, there were greater concerns regarding energy prices (4.4), personal or family health (4.3), and drug addiction (3.9). Primary environmental stressors were industrial noise (3.6) and groundwater depletion (3.5). In the Slovnaft area, there were the quality of healthcare (3.8), air pollution (3.6), odor (3.2), and industrial noise (3.1). Industrial noise was identified as a relevant environmental concern in both regions. The findings confirm the applicability of the questionnaire methodology across different industrial settings and highlight the importance of combining subjective perception data with objective noise measurements.

INTRODUCTION

Urban populations are exposed to various environmental risks, including noise. Environmental noise, including industrial noise, is considered by experts to be one of the major factors

contributing to a reduced quality of life in urban environments [1]. The World Health Organization identifies environmental noise as the second most significant environmental health burden in Europe, after air pollution [2].

Although noise from industrial activities is less prevalent than road traffic or aircraft noise, its adverse effects on the environment and human health cannot be ignored. While numerous studies have demonstrated annoyance and negative health impacts associated with road, rail, and aircraft noise, industrial noise sources—including mining activities—remain relatively underexplored [3]. Mining has a long-standing tradition in the Czech Republic and Poland, where it represents an important component of the national economy.

One of the major sources of industrial noise, particularly in the Czech Republic, is mining activity, especially surface mining. During the operation of mining equipment, exposed populations may be subjected to low-frequency noise. This issue is addressed within the framework of the project TA CzR SS05010044, “Methodology for assessing the exposure–response relationship of persons exposed to environmental noise from mining activities.”

The project is aimed at obtaining acoustic data (in situ measurements of noise sources at exposed locations) for subsequent modelling, taking into account terrain morphology and temporal changes in noise levels in the affected area. In addition, subjective data on noise annoyance are collected from residents using a standardized questionnaire.

For the purpose of validating the questionnaire methodology with respect to a different source of industrial noise, and to test its applicability beyond the Czech Republic, a collaboration was established between the Institute of Epidemiology and Public Health, Faculty of Medicine, University of Ostrava, and the Institute of Hygiene, Faculty of Medicine, Comenius University in Bratislava. Within this international cooperation, a sub-project entitled “Assessment of the Impact of Industrial Noise on Health and Quality of Life of the Population” was developed.

The present study aimed to validate the questionnaire survey methodology in the context of a different industrial noise source—specifically the Slovnaft refinery—and to compare the results with a study conducted in the vicinity of the Turów surface mine in Poland.

METHODS

Study Areas and Population

Data from the Czech Republic were collected between 2022 and 2023 from residents living near the Turów surface mine. These residents have long reported concerns about mining noise and groundwater depletion.
Slovak data were collected in 2024 from residents living near the Slovnaft refinery in Bratislava. Slovnaft is the only refinery in Slovakia and one of the most modern in Europe, processing approximately 5.5–6 million tons of crude oil annually.

Residents in surrounding districts (Podunajské Biskupice, Ružinov, Vrakuňa, Petržalka, Rusovce) and nearby municipalities reported long-term exposure to increased noise levels, strong odors, and dust [4,5]. The city district of Podunajské Biskupice is located to the east–southeast of the Slovnaft refinery in Bratislava, Slovakia. The distance between residential areas and the refinery ranges from approximately 1 to 3 km, making it one of the closest inhabited zones to the industrial site. In addition to Podunajské Biskupice, the population potentially affected by emissions from the Slovnaft refinery includes residents of the adjacent Bratislava districts of Ružinov, Vrakuňa, Petržalka, and Rusovce. These districts are located at varying distances and directions from the refinery and differ in their level of environmental

exposure depending on proximity, urban structure, and local dispersion conditions. Ružinov and Vrakuňa are situated closest to the industrial complex and are therefore considered more directly exposed, whereas Petržalka and Rusovce may be affected under specific meteorological conditions, particularly prevailing wind patterns. This spatial variability allows for the assessment of exposure gradients and differences in perceived environmental burden across residential areas surrounding a major industrial source.

The study included by now 196 respondents (59 from Turów, 137 from Bratislava). The average age was 50 years. No significant differences were observed in age, gender, marital status, or self-rated health; however, Bratislava participants had significantly higher education levels.

Questionnaire

Data were collected using a structured questionnaire consisting of five main domains, focusing on basic demographic characteristics, health status, lifestyle, quality of life, and the perception of general and environmental problems. The questionnaire was based on standardized instruments used in international projects (EHIS, CESAR, SES, and the HAIE –Healthy Aging in Industrial Environment project, SK. /0.0/16_019/0000798). The questionnaire was translated into Slovak by two independent translators, followed by revision and adaptation. It included: general questions (8 items), risk perception questions (20 general problems and 14 environmental problems assessed on a five-point Likert scale), questions on subjective health status (4 items), lifestyle questions (4 items), and overall life satisfaction/quality of life (4 items).

The questionnaire was distributed both online and in printed form. Local authorities and residents in the vicinity of the Slovnaft refinery (Podunajské Biskupice, Vrakuna, Rovinka, Dunajská Lužná) were contacted via an information letter requesting completion of an anonymous questionnaire. The survey was intended for individuals aged over 15 years, and participation was voluntary. The study was approved by the Ethics Committee of the Faculty of Medicine, Comenius University, and University Hospital Bratislava, as well as by the relevant ethics committee in the Czech Republic.

Noise Exposure Assessment

Long-term nocturnal noise monitoring was conducted in residential areas adjacent to those affected regions.

Long-term acoustic monitoring near the Slovnaft refinery was conducted between February 25 and March 31, 2022. Measurements were taken in residential areas of adjacent districts of Bratislava during the reference nighttime period (22:00–06:00), including family houses and apartment buildings in Podunajské Biskupice (the closest inhabited zones to the industrial site), and the other adjacent areas (Petržalka, newly built residential area Slnečnice), during nighttime (22:00–06:00). As part of synchronous noise monitoring, a noise compass was installed at a reference location, enabling automatic detection of both vertical and horizontal directions of dominant noise sources. The monitoring results demonstrated exceedances of permissible noise limits from refinery operations at measurement sites in Podunajské Biskupice of up to 10.3 dB [6].

The Public Health Institute, Ostrava, Czech Republic provided the noise measurement. The long-term measurement (outside the buildings) took place in five weekly cycles (April, June, July, September, October/November) during the time intervals from 10 p.m. to 6 a.m. in the

year 2022. The short-term measurement took place in three nights (2 days in June, 1 day in July 2022) inside the buildings. Short-term noise exposure limits recorded in the vicinity of the Turów mine were exceeded, but long-term noise limits were not violated [3].

Table 1: Preliminary results of long-term noise pollution

Year	Monitored area (Oldrichov)			Monitored area (Uhelna)		
	T	$L_{Aeq,T}$	L_{A90avg}	T	$L_{Aeq,T}$	L_{A90avg}
	h	dB	dB	h	dB	dB
2024	136	36.0	34.3	161	36.0	34.0
2023	171	35.5	34.4	177	36.2	34.4
2022	222	35.3	33.8	210	36.5	35.1
2021	200	35.4	33.6	175	3.,0	34.5
2020	148	37.4	35.3	144	37.7	36.1

RESULTS

A total of 59 exposed individuals from the Turów region and 137 from the Slovnaft area participated in the study. The respondents, with a mean age of 50 years, did not differ significantly in terms of age, gender distribution, marital status, self-rated health, or economic situation. The only significant difference was observed in educational level, with a higher proportion of respondents with higher education in the Bratislava region. Regarding general problems, respondents in the Turów region identified the most serious issues as “increasing energy costs” (mean 4.4 vs. 3.7 in the Slovnaft area; $p < 0.001$), “own or family health” (4.3 vs. 3.6; $p = 0.002$), and “drug addiction including AIDS” (3.9 vs. 2.8; $p < 0.001$). The perception of these issues differed significantly between the two regions (Figure 1).

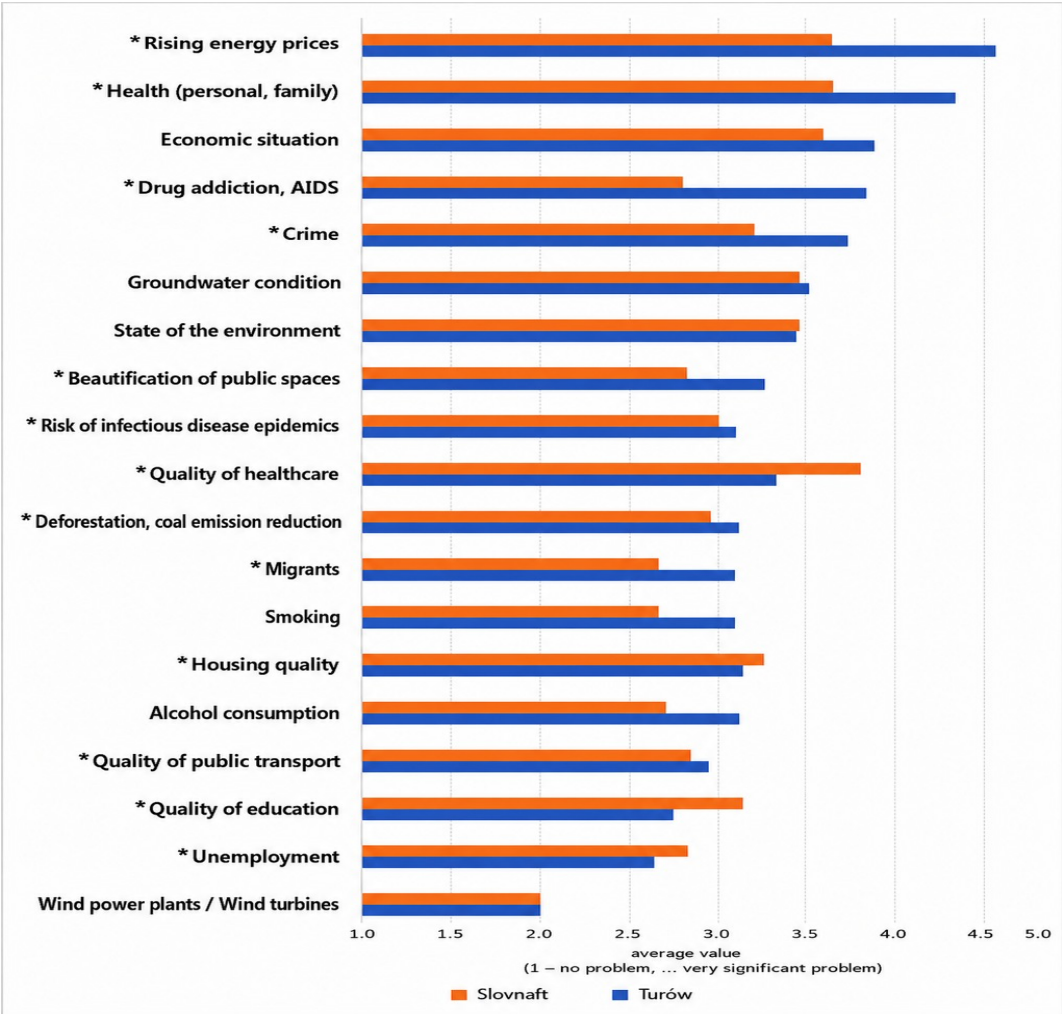

Figure 1: **General problems: comparison of Turów and Bratislava**

* - significant difference

In both study areas, the economic situation of the country was perceived as a highly serious problem (3.9 vs. 3.7; $p = 0.386$). The least serious general risks reported by respondents in the Turów region were “unemployment” (2.5 vs. 2.8; $p = 0.179$) and “wind power plants” (both regions 2.0; $p = 0.924$). In contrast, respondents from the Slovnaft area rated “quality of healthcare” as the most important general issue (3.8 vs. 3.3 in Turów; $p = 0.010$). Concerning environmental problems at the place of residence (Figure 2), respondents from the Turów region considered the most serious issues to be “industrial noise” (3.6 vs. 3.1 in the Slovnaft area; $p = 0.018$), “groundwater depletion” (3.5 vs. 2.2; $p < 0.001$), and “dust in the residential environment” (3.4 vs. 2.8; $p = 0.004$).In contrast, respondents from the Slovnaft area perceived “air pollution at the place of residence” (3.6 vs. 3.1 in Turów; $p = 0.009$) and “odor in the residential environment” (3.2 vs. 2.4; $p < 0.001$) as the most significant environmental problems, followed by industrial noise. The least significant environmental problem for respondents in the Turów region was “street noise” (1.7 vs. 2.4 in the Slovnaft area; $p < 0.001$), whereas respondents in the Slovnaft area considered “lack of drinking water at the place of residence” to be the least serious issue (1.7 vs. 2.3 in Turów; $p = 0.006$) (Figure 2).

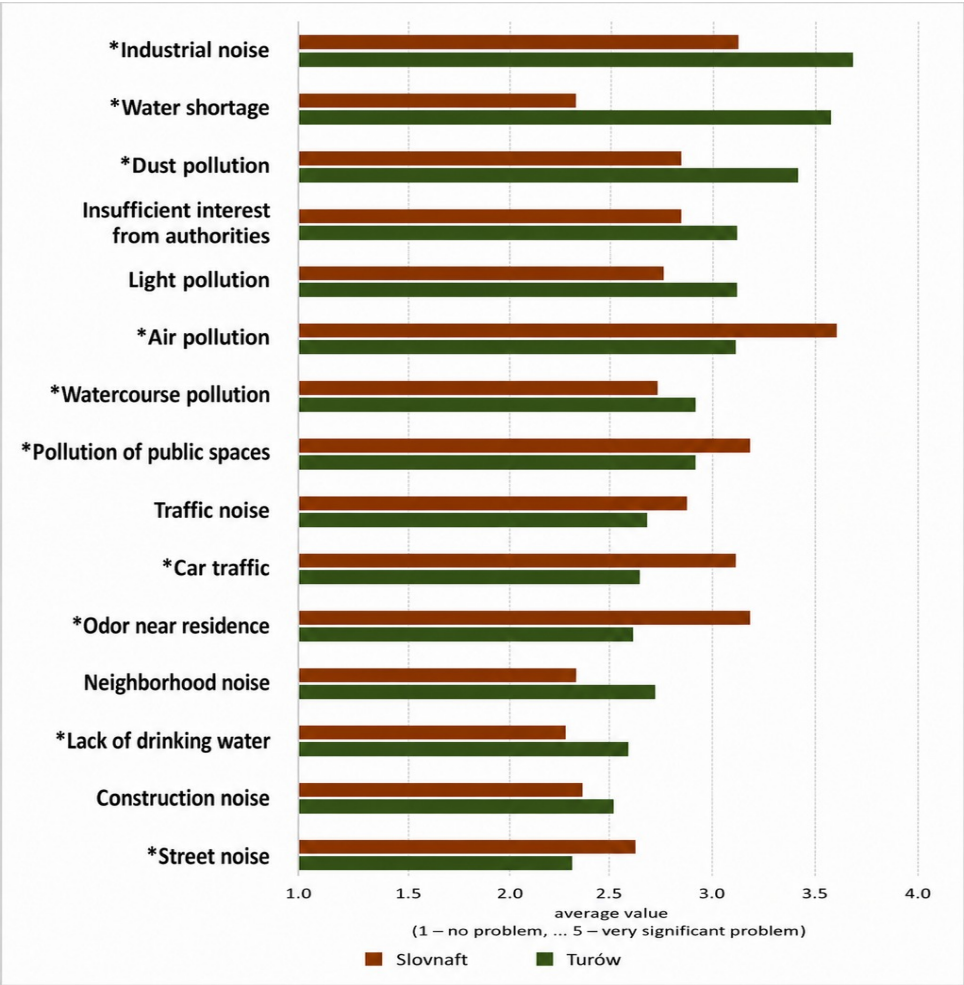

Figure 2: Environmental problems: comparison of Turów and Bratislava

* - significant difference

DISCUSSION

The present study confirmed significant regional differences in the perception of environmental and societal problems between residents living near the Turów surface mine and those residing in the vicinity of the Slovnaft refinery. The findings indicate that perceived environmental burden is influenced not only by the physical characteristics of industrial exposure, but also by broader socio-economic and local contextual factors.

Residents of the Turów region perceived industrial noise, groundwater depletion, and dust as the most serious environmental concerns. These findings are consistent with the specific environmental impacts typically associated with surface mining activities, particularly low-frequency noise, landscape transformation, and changes in groundwater regimes [3,7]. Long-term exposure to mining operations may increase residents' awareness of environmental degradation and contribute to higher levels of annoyance and perceived health risk. Similar observations have been reported in studies examining communities exposed to industrial and mining-related noise, where subjective annoyance was influenced not only by measured noise levels but also by perceived environmental injustice, non-acoustic factors, and reduced trust in environmental management [3,8,9]. Furthermore, exposure to low-frequency industrial noise has been associated with annoyance, sleep disturbance, impaired well-being, and stress-related symptoms in exposed populations [10,11]. In contrast, respondents living near the

Slovnaft refinery emphasized air pollution, odor, and industrial noise as the most important environmental problems. Odor perception appears to play a particularly important role in refinery-affected urban areas because odor is often interpreted by residents as an indicator of harmful chemical exposure, even when objective pollutant concentrations remain within regulatory limits [12,13]. Previous studies have shown that odor annoyance may substantially contribute to stress, reduced well-being, sleep disturbance, psychological distress, and lower residential satisfaction in populations living near industrial facilities [13–16].

Although industrial noise was identified as an important environmental burden in both regions, differences in annoyance patterns may reflect variations in the acoustic characteristics of the noise sources. Mining operations are frequently associated with low-frequency and continuous noise exposure, whereas refinery-related noise is often combined with intermittent technological operations and additional sensory stressors such as odor and air pollution. The cumulative effect of multiple environmental exposures may therefore enhance subjective annoyance among residents in urban-industrial environments.

The study also demonstrated that environmental perception is closely connected with societal and economic conditions. Respondents from the Turów region expressed stronger concerns regarding increasing energy costs, health status, and drug addiction, whereas respondents from Bratislava emphasized healthcare quality. These differences likely reflect the timing of data collection, regional socio-economic conditions, and differing public concerns in the Czech–Polish border region and the Slovak urban environment.

An important strength of the study is the application of a standardized questionnaire methodology in two industrially burdened regions with different environmental exposure profiles. The results support the applicability of the questionnaire beyond the original Czech setting and demonstrate its usefulness for assessing subjective environmental burden in populations exposed to industrial noise.

Several limitations should also be acknowledged. The study relied on subjective self-reported data, which may be influenced by personal attitudes, media coverage, and current socio-political conditions. In addition, the relatively limited sample size may reduce the generalizability of the findings. Future research should combine questionnaire-based assessments with detailed acoustic modelling, long-term environmental monitoring, and objective health indicators in order to better understand exposure–response relationships associated with industrial noise.

Overall, the findings highlight the importance of considering both objective environmental exposure and subjective community perception in environmental health risk assessment and in the development of targeted preventive and mitigation strategies for populations living near major industrial sources.

CONCLUSION

The study confirmed the expected major environmental problems in both investigated areas. While residents living near the Turów surface mine primarily perceived problems associated with mining activities, particularly industrial noise and groundwater depletion, respondents from the vicinity of the Slovnaft refinery also expressed concerns of a broader socio-economic nature. Among environmental problems, odor, air pollution, and industrial noise were identified as the most important issues in the Bratislava region.

Despite the presence of environmental burdens such as noise and odor, residents perceived these problems within a wider social and economic context. In the Turów region, increased energy prices and concerns about health related to the COVID-19 pandemic represented important societal issues. In contrast, respondents from Bratislava, where the survey was conducted in 2024, more frequently emphasized concerns regarding healthcare quality and economic stability in relation to ongoing political changes.

The study also demonstrated the applicability of the standardized questionnaire methodology in different industrial environments and supported its use for assessing environmental annoyance and perceived health risks in exposed populations. The combination of subjective perception data with environmental monitoring may provide valuable information for environmental health risk assessment and for the development of targeted preventive and mitigation strategies.

The findings indicate that the perception of environmental burden is influenced not only by objective environmental exposure but also by current social, economic, and political conditions. These results highlight the importance of integrating environmental, social, and public health perspectives in the assessment and management of industrially burdened areas.

Further research should focus on integrating questionnaire-based assessments with detailed acoustic modelling, long-term environmental measurements, and objective health indicators in order to better understand exposure–response relationships associated with industrial and low-frequency noise exposure.

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Trends in leisure-time noise exposure among university students

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ABSTRACT

The study aimed to analyse the trend in noise exposure from leisure-time activities among medical students with permanent or temporary residence in Bratislava over 10 years. We focused on the frequency and intensity of listening to personal music players (PMPs), attendance at events with high sound intensity, and monitored subjectively reduced hearing ability. We used the subjective assessment method using the "Noise Annoyance Questionnaire". Respondents subjectively rated the intensity and frequency of exposure, their preferred type of headphones, player volume level, and how often they attend high-sound events. Respondents subjectively rated the intensity and frequency of exposure, preferred type of headphones, player volume level, and how often they attend events, as well as exposure from traffic noise. Based on data collected from a validated questionnaire, we evaluated environmental, behavioural, and psychosocial factors in respondents in relation to noise exposure. The data were analysed using the IBM SPSS 29 statistical program.

The study included 2,920 medical students, 69.5% females and 30.5% males. The mean age was 23.2 ± 1.8 years. The increasing trend in the use of PMPs ($p < 0.01$) was observed. Of the total number of PMP users, 34.3% exceeded the LAV (lower action value for industry, $L_{AEX,\,8h}$= 80 dB) for noise exposure.

Preliminary results of the 10-year study showed that respondents used PMPs more frequently, and simultaneously, the duration of their listening increased. High noise exposure among youngsters highlights the need for effective noise mitigation and systematic health impact monitoring.

INTRODUCTION

According to the World Health Organization, more than 1 billion young adults are at risk of permanent or partial hearing loss due to prolonged exposure to high-volume music through personal audio devices. Noise-induced hearing loss (NIHL) results from metabolic and

mechanical damage to the organ of Corti, leading to a shift in hearing thresholds. Regular or long-term exposure to loud sounds can permanently damage hair cells and other structures within the cochlea, resulting in irreversible hearing impairment. Initially, the high-frequency range is primarily affected; however, continued exposure leads to further auditory degradation. Young adults frequently utilize personal music players and frequent venues with high sound pressure levels, which significantly increases the risk of auditory damage [3, 4]. Given the potential health consequences of long-term exposure to excessive noise, it is essential to recognize that acoustic energy doubles with every 3 dB increase. Consequently, each 3 dB increment in sound level halves the permissible exposure time. If the allowable exposure at a noise level of 85 dB is 8 hours, at 94 dB, it is reduced to only 1 hour, and at 106 dB, it is approximately 3.75 minutes [5].

AIM OF STUDY

The study aimed to analyse the trend in noise exposure from leisure-time activities among medical students with permanent or temporary residence in Bratislava over 10 years. We focused on the frequency and intensity of listening to personal music players (PMPs), attendance at events with high sound intensity, and monitored subjectively reduced hearing ability.

MATERIAL and METHODS

The study sample consisted of a homogeneous group of young adults, characterized by relative uniformity in terms of age, educational level, lifestyle, and health status. All participants had completed secondary education and were engaged in mental work within non-noisy environments. The study included 2,920 fourth-year students from the Faculty of Medicine at Comenius University in Bratislava, with either permanent or temporary residence in Bratislava. The demographic composition of this population group was predominantly female (69.5%), while males accounted for 30.5% of the cohort. The mean age of the respondents was 23.2 ± 1.8 years, reflecting the typical age structure of university students. The homogeneity of the sample allowed for the minimization of socio-demographic variations influencing the assessed noise exposure indicators and related factors.

Table 1: Composition of student groups by gender and mean age across individual years

Year	Gender		Smoking			Alcohol consumption		
	Male %	Female %	Never smoked %	Quit smoking %	Smoke regularly %	Abstainer %	Occasionally%	Daily %
2014	30,2	69,8	71,9	10,7	17,4	7,3	88,6	4,1
2015	24,0	76,0	79,4	10,5	10,1	6,9	90,3	2,9
2016	36,0	64,0	79,2	9,1	11,7	9,4	86,7	4,0
2017	28,4	71,7	79,5	9,9	10,7	6,8	90,7	2,4
2018	26,9	73,1	77,7	8,4	13,9	9,5	87,6	2,9
2019	30,9	69,2	76,5	11,2	12,3	9,6	85,1	5,3
2022	31,2	68,8	78,0	10,4	11,6	9,1	80,2	2,7
2023	30,9	69,1	77,0	11,2	11,8	10,1	87,3	2,6
2024	32,8	67,3	73,0	14,8	12,2	9,0	89,3	1,7
2025	31,0	69,0	77,7	11,4	10,9	16,0	80,8	3,3
p-value	0,13		0,35			0,08		

Students completed a standardized, validated, and anonymous "Noise Annoyance Questionnaire," developed by experts at the Institute of Hygiene, Faculty of Medicine, Comenius University in Bratislava. The questionnaire consisted of 73 questions focused on health status, lifestyle, and psychosocial well-being in relation to noise exposure. Respondents assessed voluntary noise exposure, such as the use of personal music players and attendance at high-noise-level events. Responses were quantified using subjective intensity ratings.

To evaluate the impact of noise, a 5-point noise interference and annoyance scale was used, following the recommendations of the ICBEN (International Commission on Biological Effects of Noise) expert team [6]. Respondents assessed the impact of noise on their overall state, as well as the interference and annoyance caused by traffic noise. The scale was as follows: 0 = not at all, 1 = slightly, 2 = moderately, 3 = very, 4 = extremely.

To assess the volume settings of personal music players, a 4-point scale was used:

= music is no louder than human speech,

= music volume usually allowed conversation to be heard,

= music volume usually allowed a passing car to be heard,

= music volume usually prevented hearing either conversation or traffic noise.

The frequency of exposure was also evaluated. Data collection spanned a 10-year period, from 2014 to 2025; however, no data were collected during 2020 and 2021 due to the pandemic and associated restrictive measures. Data analysis was performed using IBM SPSS Statistics version 29.0, utilizing descriptive statistics and custom tables. The significance of patterns and differences was tested using the Chi-square test and Cochran-Mantel-Haenszel statistics.

RESULTS

The results indicate an increasing trend in the use of personal music players (PMPs) ($p < 0.01$) during the monitored period. In 2025, 86.9% of students used personal players, compared to only 76.8% in 2014 (Figure 1).

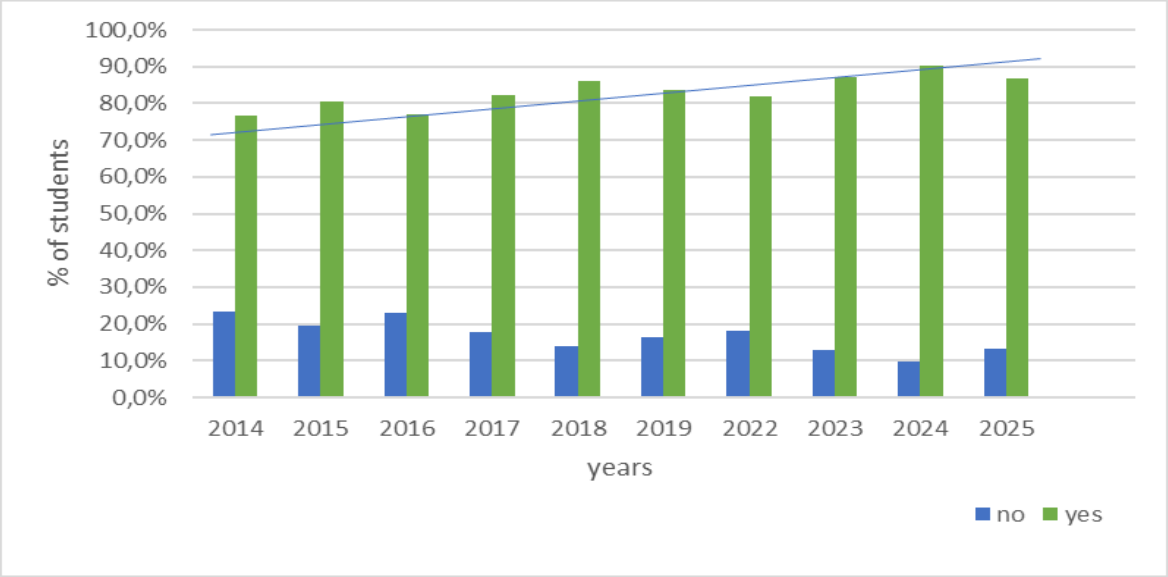

Figure 1: Trend of Personal Music Player Usage, 2014 – 2025.

Students most frequently preferred in-ear (intra-aural) headphones. At the maximum volume setting, these headphones produce a sound pressure level of 97.8 dB, based on exposure dose calculations according to Portnuff [1, 2]. For over-ear/on-ear headphones (supra-aural/circum-aural), the sound pressure level reaches 101 dB at the maximum volume setting. Both groups most commonly set the volume to a medium level: 73.2 dB in the in-ear group and 76.4 dB in the over-ear group. Users of over-ear headphones were statistically significantly more likely to set the volume to the highest level (i.e., 101 dB). The comparison of students using in-ear versus over-ear headphones, along with their respective volume levels, is illustrated in Figures 2 and 3.

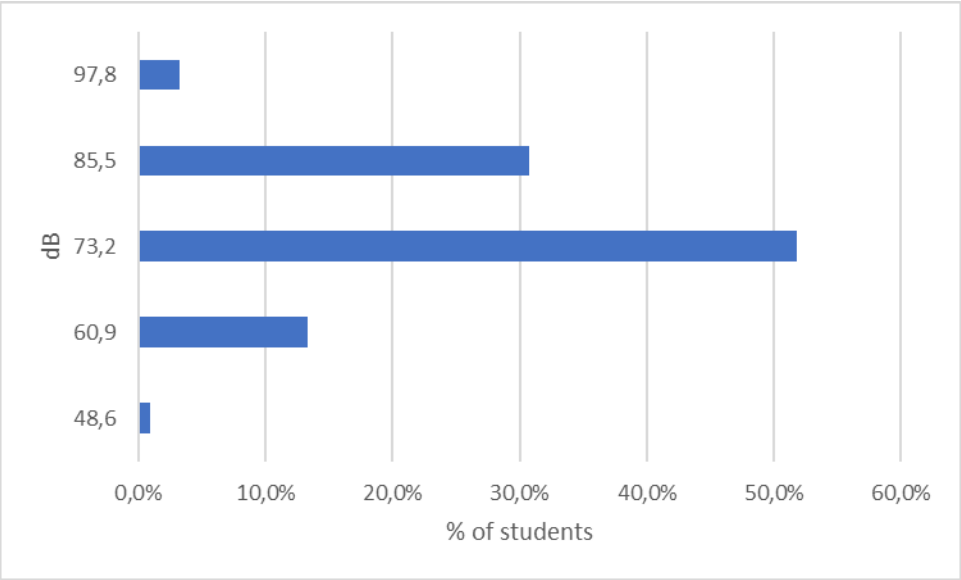

Figure 2: Students listening to personal music players through earphones.

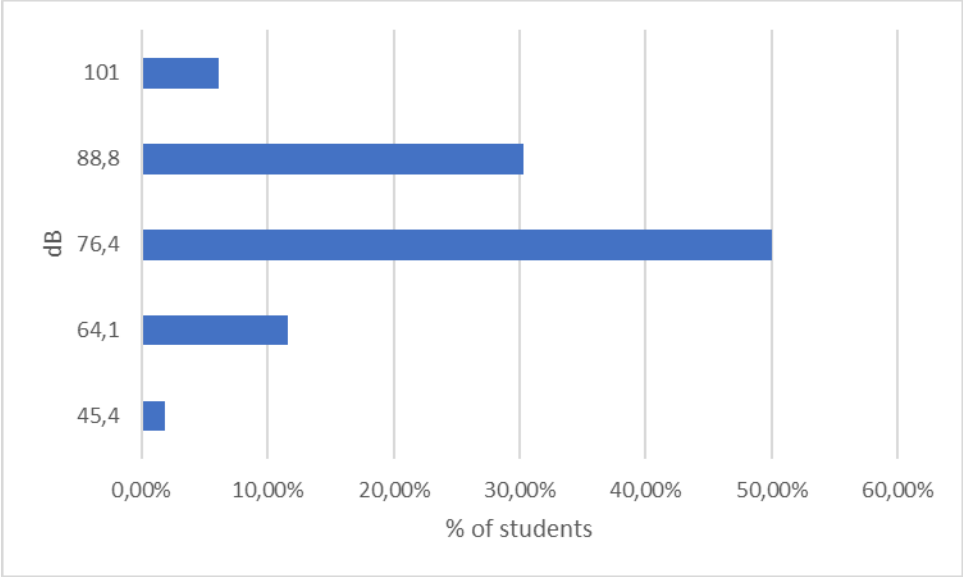

Figure 3: Students listening to music players using headphones.

Our study also recorded an increase in the duration of PMP listening in minutes per week. The longest listening duration was observed in 2025, with students listening to PMPs for an average of 414.55 minutes per week (Figure 4).

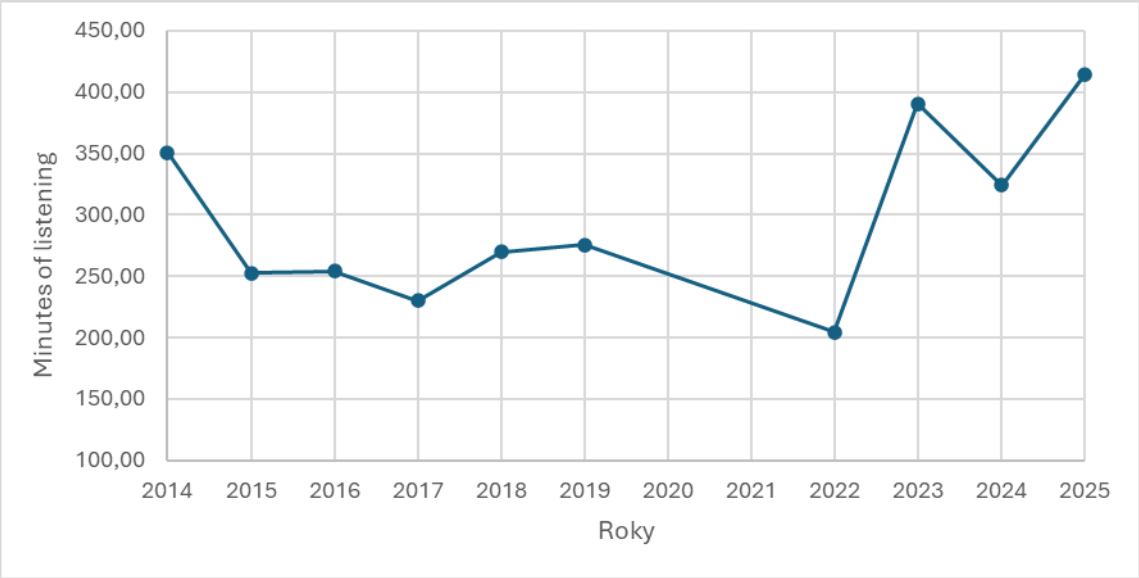

Figure 4: Average listening times of personal players for individual years in minutes.

Regarding other leisure-time activities with increased noise exposure, students most frequently engaged in household chores with noisy appliances (vacuum cleaners, lawnmowers, or drills), followed by visits to the cinema and discotheques (Figure 5).

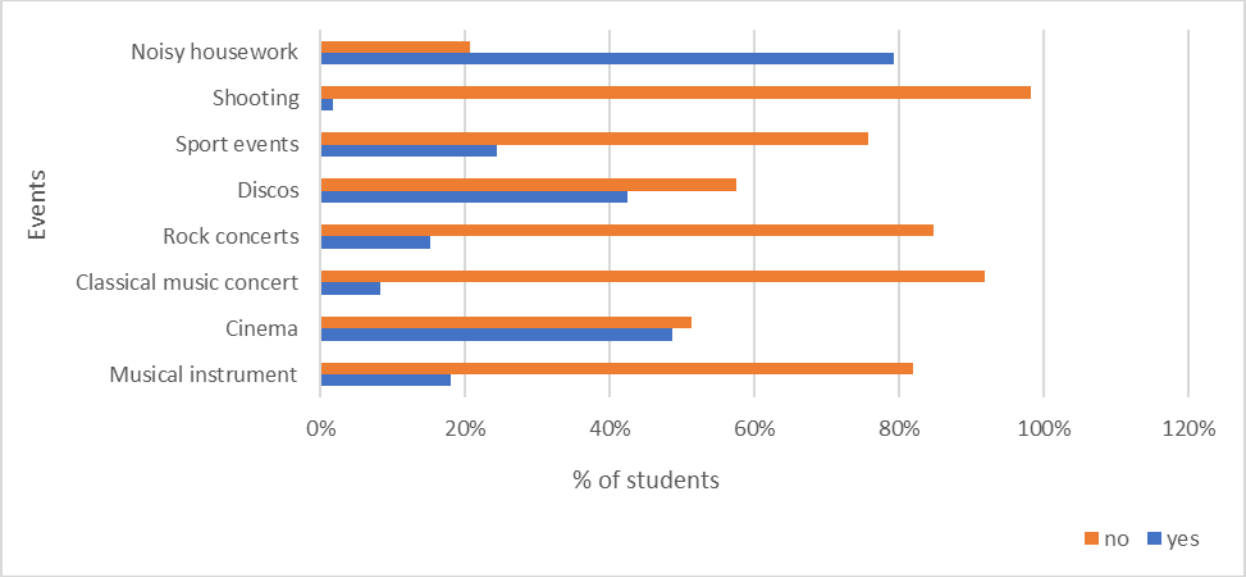

Figure 5: Overview of leisure activities with higher noise exposure per month.

Year-on-year, we recorded a decline in noise exposure from leisure-time activities as the interest in these activities decreased (Figure 6). A significant decline was noted in playing musical instruments, while visits to discotheques and sports events also showed a downward trend. Cinema attendance remained stable.

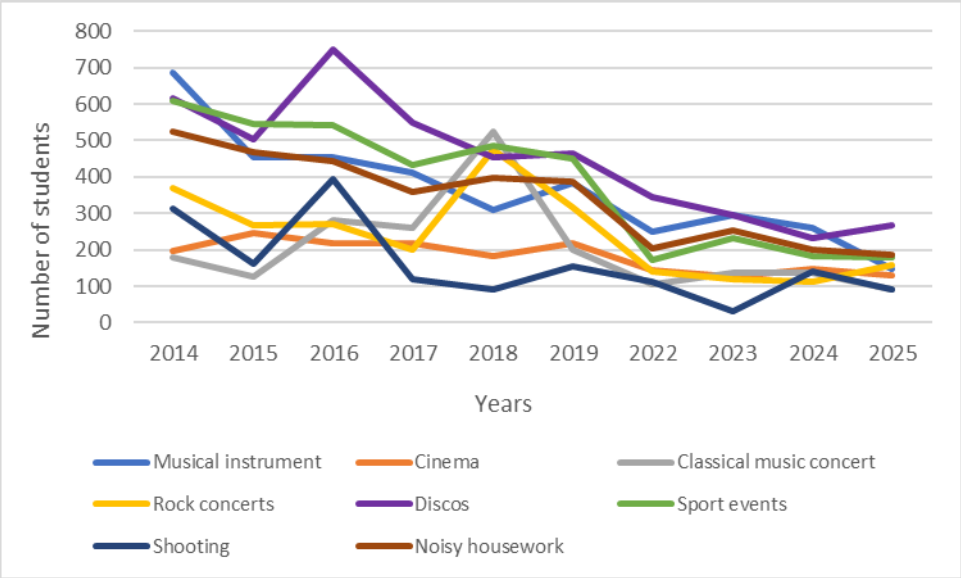

Figure 6: Trends of leisure time activities in the years 2014-2025.

DISCUSSION

The increase in PMP usage from 76.8% to 86.9% in our cohort correlates with findings reported by Engdahl [8], who noted an increase in PMP use from 8% in 1998 to 30% in 2018. Engdahl further stated that while low to moderate volume settings do not show a strong correlation with hearing impairment, users of PMPs set to high volumes exhibited increased hearing thresholds. This is further supported by Filová et al. [7], who investigated audiometric thresholds in medical students and found impaired hearing at higher frequencies (6000 Hz

and 8000 Hz bilaterally) as well as at lower frequencies (1000 Hz in the right ear and 2000 Hz bilaterally).

In our study, measured sound pressure levels at maximum volume ranged from 97.8 to 101 dB. These values significantly exceeded the preventive recommendations of the World Health Organization (WHO), which suggests that PMP volume should not exceed 60% of the maximum [9]. Portnuff [10] recommends setting the volume to 80% for a maximum of 90 minutes per day. The risk in our cohort is exacerbated by the observed increase in average listening time to over 414 minutes per week in 2025.

High sound levels capable of permanently damaging hearing also occur during leisure-time activities such as concerts, nightclubs, or sports stadiums. According to Balko [13], sports events can reach noise levels of 95–104 dB, while rock concerts or car stereos can reach up to 120 dB. Chung et al. [14] reported that approximately half of respondents (n = 9,693) experienced a temporary threshold shift (TTS) and transient tinnitus after attending concerts or nightclubs.

These events may cause irreversible damage to specific regions of cochlear hair cells and auditory nerve fibers in susceptible individuals. Although audiometric thresholds may temporarily recover and tinnitus symptoms may disappear, repeated exposure can lead to cumulative damage and eventually result in chronic hearing impairment [15,16]. As a preventive measure, Jiang [11,12] recommends the use of noise-canceling headphones, which reduce surrounding environmental noise and may lower listening volumes by approximately 4 dB.

CONCLUSION

Based on the results of our study, we can conclude that year-on-year, medical students show a declining interest in leisure-time activities with high intensity of noise exposure, but an increasing use of personal music players with headphones, which are often set to higher volume levels. This trend is likely related to the widespread availability of players through smartphones and headphones, as well as the ability to connect to publicly available Wi-Fi networks. We recommend setting safe maximum volume limits whenever the device allows it and taking regular breaks during prolonged listening. It is also advisable to reduce attendance at events with high noise exposure or to shorten the duration of exposure. Following exposure to intense noise, the auditory system should be allowed a recovery period of 12–24 hours in a quiet environment.

Future research will focus on the assessment of audiometric thresholds using pure-tone audiometry.

Acknowledgements

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Impact of the auditory environment on cognitive performance and behaviour in schools/workplaces: Methodological review 2023-2026

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ABSTRACT

Our auditory environment can impact our cognitive performance and behaviour. In academic research, a multitude of measures can be used to assess performance and behaviour, and a diversity of sounds can be generated, recorded, and manipulated. This paper addresses the question: What methods were used in the research published between 2023-2026 that examine the impact of the auditory environment on performance and behaviour? It uniquely covers both school environments (with participants under 18) and workplaces (with adults). Following the scoping review PRISMA protocol, four databases were searched (MEDLINE Complete, PsychInfo, Scopus, Web of Science). Selected articles had to: (1) be peer-reviewed journal articles published in English; (2) include at least one objective measurement of sound; (3) present at least one experimental comparison which varied the characteristics of the stimulus; (4) report at least one quantitative or qualitative measure of cognitive performance/process. Articles that only reported neurophysiological measures, focused on cochlear implants, or measured speech intelligibility/listening comprehension were excluded. 105 papers met inclusion criteria: 18 about schools, 87 about workplaces. Participants, sound conditions, performance measures, study design were charted and summarised. Studies investigating the impact of chronic (long-term) exposure to sounds had larger sample sizes compared to studies on acute (short-term) exposure. There is a balanced use of environmental and speech sounds in school and workplace studies, with artificial sounds being more frequently used in workplace studies. Recommendations for future studies are to embrace neurodiversity instead of excluding participants with neurodevelopmental conditions, and to consistently compare objective and subjective performance measures.

INTRODUCTION

This review is led by the International Commission on Biological Effects of Noise (ICBEN) Team 4. The team focuses on understanding the impact of noise on performance and behaviour [1-2].

ICBEN defines noise as a sound that is unwanted and/or harmful due to its intensity [3]. In schools and workplaces, unwanted sounds include people passing by, overheard conversations, sounds from mechanical devices (e.g. printers, ventilation, fridge) and tools (e.g. keyboards, jackhammers). Noise is partly subjective which is why a more neutral concept of "sound" will instead be used throughout the review. Sound is defined as mechanical vibrations that are travelling through the air and can be heard [4]. This neutral term offers the opportunity to express: (1) complexities about what features of the auditory stimulations may affect performance and behaviour; (2) situations in which subjective and objective effects do not align.

The aim of the review is to provide a methodological overview of the literature published in the field between 2023 and 2026, extending [1-2]. The paper addresses the following research question: What methods were used in the research investigating the impact of the auditory environment on cognitive performance and behaviour, between 2023-2026? Methods include: participants, sound conditions, performance measures, and study design. For the first time, the ICBEN Team 4 review includes studies with children under 18 in school settings as well as adults in the workplace.

METHODS

The search terms were replicated from [1], with the last keywords being adapted to represent the school/workplace contexts:

ALL=("Noise" OR "Sound") AND

ALL=("Cognitive Performance" OR "Cognitive work" OR "Cognitive activity" OR "Cognitive ability" OR "Cognitive task" OR "Mental work" OR "Mental task" OR "Mental processing" OR "Memory task" OR "Working memory" OR "Executive function" OR "Attentional focus" OR "Attentional capture" OR "Problem solving" OR "Adaptive behaviour" OR "Human behaviour" OR "Speech intelligibility" OR "Coping") AND

[For children's review:] ALL=("School" OR "Classroom")

[For adults' review:] ALL= ("Work" OR "Job" OR "Public place" or "In public" OR "dwelling" OR "Building acoustics")

The search was carried out on MEDLINE Complete, PsychInfo, Scopus, Web of Science. It covered the period from 3rd March 2023 to 1st February 2026. Only peer-reviewed journal articles published in English were included. Papers on school settings must have included participants under 18 years of age. Papers on workplaces must have participants above 18 years of age.

In addition, papers must have reported:

- At least one objective, replicable measure of sound (this included either: the sound pressure level, spectral characteristics, frequency, source of noise, content of noise)
- At least one quantitative or qualitative (interview, observation) measure of cognitive performance (as defined by the keywords) - objective or subjective

- At least one experimental comparison which varies the characteristics of the stimulus, either within or between subjects

Additional exclusion criteria were: (1) Papers already included in [1]; (2) Papers which only reported neurophysiological measures; (3) Papers which solely focused on cochlear implants, speech perception, speech intelligibility, which fall within the remit of ICBEN Teams 1 and 2.

For the review on school settings, the database searches retrieved 886 papers, leading to 813 after duplicates were removed on Zotero. Following abstract screening, 63 papers met the criteria for full-text screening, of which 18 papers met the criteria to be included in the review.

For the workplace review, database searches retrieved 1,260 papers, leading to 1,178 after duplicates were removed on Zotero. Following abstract screening, 143 papers met the criteria for full-text screening, of which 87 papers met the criteria to be included in the review.

RESULTS

Children's performance in noise in school settings

Participants. As shown in Table 1, the majority of studies covered primary school years.

Table 1: Age of the participants included in the studies.

Pre-primary (3-5)	Primary (6-11)	Secondary (12-17)	Longitudinal	Cross sectional wider ranges
[5]	[6-12]	[13-15]	Covering 3-17 [16] Covering 0-13 [17]	Covering 6-13 [18] Covering 8-21 [19] Covering 8-17 [20] Covering 7-14 [21]

Age bands corresponding to school levels were taken from UNICEF [22].

The majority of studies ensured that participants did not have a hearing impairment [6-13], [18], [20-21], [23]. Six studies excluded data from children with neurodevelopmental conditions [5-6] [10-11], [13], [19]. Other exclusion criteria were learning disabilities [8], [11]; language delays [6], [18], [20]; epilepsy [9]. Three studies checked that children had a certain level of cognitive abilities [12], [18-19] and normal or corrected-to-normal vision [7], [11-12]. Two studies explicitly compared autistic and non-autistic children [18], [21]. One study compared children with and without Attention Deficit Hyperactivity Disorder (ADHD) [12]. Special schools were included in [16] and no exclusion was reported in [5], [14-15], [17]. Sample sizes ranged from 35 [9] to 12 130 [5]. Sample sizes varied according to study design. Studies focusing on acute sound exposure involved 108 children on average (median: 114, min: 35, max: 229). Studies looking into chronic sound exposure involved more participants: 4 863 on average (median: 1524, min: 131, max: 12 159).

Sound conditions. Eleven studies focused on acute sound exposure, using short-term experiments to expose participants to various sound conditions [6-7], [9-13], [18-21]. The most commonly used sound stimulus was multi-talker babble noise [6], [9-11], [20]. Also in use were single-talker speech [7], [18], [21]; classroom noise [18]; environmental sounds [7], ventilation [13], music [21]; animal sounds [21]; white noise [18]; pure tones [12] and stimuli of varying emotional intensity [19]. The sound stimuli ranged from 33dB [10] to 77dB [19]. The majority of the 11 experimental studies included a quiet control condition [6-7], [9-11], [13], [18], [20].

Seven studies looked at chronic sound exposure, meaning long-term exposure corresponding to real-life conditions [5], [8], [14-17], [23]. Among these, three studies focused on the association between exposure to traffic sounds [16-17], residential sounds [5] and performance outcomes. Four studies adopted a semi-experimental design, investigating the impact of sound amplification systems implemented in classrooms [23], or comparing prevailing sound conditions in classrooms with a quieter [14-15] or louder [8] condition.

Measures of performance and behavior. The studies which focused on chronic exposure to transportation sounds and did include children with neurodevelopmental conditions used extensive cognitive test batteries as outcome variables [5], [14-17]. The other two studies looking into long-term sound exposure in the classroom measured reading fluency [23], working memory and long-term memory [8].

Experiments with acute sound exposure used: calculation [13]; listening comprehension [10]; reading comprehension [10], [13], [18]; recall [6-7], [9], [11], [18]; attention [11-12], [20]; auditory emotion recognition [19]; change deafness [21] tasks as outcome variables.

Adult performance in noise

Participants. The average number of participants in laboratory studies was 49 (median: 40; min: 10; max: 192) while it was 199 for field studies (median: 119; min: 31; max: 828).

Sound conditions. Of 87 studies, 72 were laboratory studies examining mostly the acute effects of the sound environment and 15 were field studies examining mostly chronic effects. Table 2 reports the studies per sound type – see Figure 1 for overall numbers. The most common sound types were environmental sound (42 studies), speech (39 studies) and artificial sounds (32 studies). Environmental sounds consisted of everyday life sounds, such as occupational noise, which were examined in field [24-32] and laboratory studies [33-48]. Traffic noise was another common noise type examined mostly in laboratory studies ([35], [37], [49-58]) but also field studies ([25], [77], [59]). Artificial sound conditions were used mainly in basic research studies investigating the effects of sound type and sound pressure level, typically by comparing specific sound environments with white, pink, or speech-shaped noise [36-37], [51-52], [60-73], [79].

Table 2. Sound conditions used in laboratory and field studies with adults.

Sound condition type	Laboratory studies	Field studies
Environmental sound	[33-58], [60], [66], [74-77]	[24-32], [59], [77]
Speech	[35], [37], [39], [40], [42], [45-46], [50-51], [53-55], [66], [68-70], [72], [74], [78-93] [110]	[30], [61], [94-95]
Artificial sound	[36-37], [51-52], [60], [62-73], [79], [91], [93], [96-105]	[61], [95]
Music	[59], [64], [67], [71], [74], [97], [106-108]	[30], [59], [109]
Nature sound	[52], [55], [60], [71]	

Measures of performance and behavior. The cognitive performance types identified were memory (39 studies), perception (30 studies), attention (30 studies), problem solving/processing (26 studies), subjective experience related to performance (26 studies) and psychomotor performance (7 studies) (see Table 3 and Figure 1). Memory performance was most examined, especially in laboratory studies. Memory performance included mostly working memory tasks

[32-33], [35], [40-41], [55-56], [59], [63], [69], [70-71], [74], [79], [81-85], [94], [96-99], [105] or free recall [45-46], [50-52], [55-56], [62], [64], [67], [72], [78], [80], [84], [106-107]. Attention was often examined in laboratory tasks for example with tests examining sustained attention [37-38], [43], [45], [47], [50], [53], [57], [60], [90-92], [97], [103-104] or Stroop or other tests measuring inhibition [24], [40], [56], [65], [74], [90], [92]. Seven out of the 15 field studies only used subjective experience as a performance measure [25-26], [28-29], [77], [95], [109]. Perception consisted mostly of detection tasks [24], [38], [44-45], [50], [54].

Table 3. Performance measures used in laboratory and field studies with adults.

Performance measure type	Laboratory studies	Field studies
Memory	[33], [35], [40], [41], [45-46], [50], [51], [52], [55-56], [60], [62], [63], [64], [67], [69], [70-72], [74], [78-79], [80-85], [96-99], [105-107]	[32], [59], [94]
Perception	[37-39], [44], [45], [47-48], [50], [53-55], [68-69], [72-73], [78], [86],-90], [96], [100-102], [108]	[24], [27], [62], [94]
Attention	[37], [38], [40], [43-45], [47], [50], [53], [55-57], [60], [65], [70], [74]-75], [76], [90-93], [97-98], [101], [103-104]	[24], [27], [30]
Problem solving/ processing	[34], [35], [36], [37], [38], [42], [45], [46], [47], [48], [49], [50], [55], [60], [68], [70], [72], [74], [83], [84], [86], [92], [106]	[24], [32], [61]
Subjective experience	[33-35], [39], [41], [45-46], [50], [55-58], [65-66], [71], [73-74], [85], [89]	[25-26], [28-29], [77], [95], [109]
Psychomotor	[36], [50], [54], [63], [87], [106], [108]	

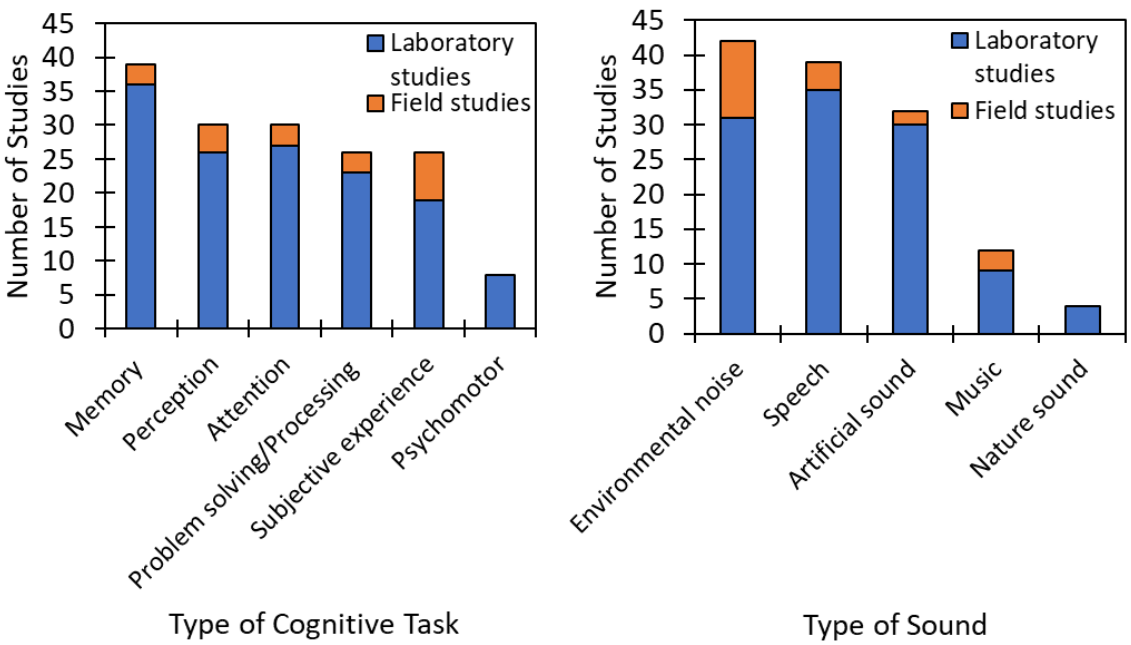

Figure 1: Number of studies per type of cognitive task and type of sound, for laboratory and field studies with adults.

CONCLUSIONS

Children

Studies focusing on the chronic impact of sounds on performance have larger sample sizes, are more likely to include children with neurodevelopmental conditions and to use extensive batteries of cognitive tests. Studies using acute sound exposure need to include more children with neurodevelopmental conditions, cognitive and language delays. This gap in the literature had already been identified three years ago [111-113].

Adults

Memory was the most examined cognitive function with both working memory and free recall being emphasized. The most common combination was examining memory performance in relation to speech sound, but only in laboratory studies. Attention and perception as well as problem solving or processing had a wider variety of tasks included.

In field studies, subjective experience was still the most common performance measure. Subjective experience related to performance was less often examined in laboratory studies which concentrated on objective performance measures. Similar results were reported in the last ICBEN Team 4 review [1]. Methodologically, this discrepancy may reflect the tradition in basic research of addressing research questions using objective measures as the preferred source of evidence [1]. It is advised to combine both objective and subjective measures in future research, in order to have a full picture of the impact of sounds on adults' performance and subjective experience.

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Assessment of the impact of partition layouts on workers' performance and perception of privacy, fatigue and workload in open-plan offices

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ABSTRACT

Privacy is often perceived as insufficient in open-plan offices. Increasing the height of acoustic partitions can improve this aspect, but at the risk of reducing overall satisfaction by creating a feeling of confinement. This study aims to examine the effects of different partition configurations on the perception of the physical environment. It was conducted in a laboratory with 36 normal-hearing participants who were asked to perform a press review task over three half-day periods, with different acoustic partition configurations (1.3 m full-height, 1.3 m with a 20 cm glazed upper section, and 1.1 m full-height). The sound environment combined speech noise with stationary background noise, resulting in Speech Transmission Index (STI) values of 0.47, 0.54 and 0.70, respectively. Fatigue, mental workload, and satisfaction with the privacy and the work environment were assessed subjectively using surveys, while performance was evaluated using multiple-choice questionnaires based on the articles read. A repeated-measures one-way ANOVA was performed for each variable, with partition as the within-subject factor. Several significant differences ($\alpha = 0.05$) were observed between the high and low partitions, as well as between the semi-glazed and low partitions, particularly with regard to overall satisfaction, acoustic satisfaction, noise annoyance, noise fatigue, acoustic privacy, visual annoyance, and visual fatigue. Results suggest that the use of low partitions in open-plan offices may be inappropriate for tasks requiring concentration. Moreover, the findings raise questions about the relevance of using high or semi-glazed partitions, particularly in terms of visual and acoustic privacy.

INTRODUCTION

In open-plan offices, partitions are often installed between workstations to reduce noise exposure and enhance employees' sense of privacy [1]. However, these partitions may also be perceived as disturbing by employees, as they can reduce visibility or create a feeling of confinement [2]. Therefore, the height and composition of partitions represent a major factor in ensuring good workstation satisfaction. Ultimately, this research will provide recommendations for office layout in open-plan environments in order to improve employees' working conditions.

Its objective is to evaluate the effect of different office partition configurations on two levels: the objective measurement of workers' performance and the subjective assessment of satisfaction with the environment and privacy, as well as fatigue and mental workload, during the achievement of a complex and extended task in a noisy open-plan office.

METHODS

Experimental conditions

In a laboratory, each participant performed a task under three partition configurations. The first partition (high configuration), with a height of 1.3 meters from the floor, is made of sound-absorbing and insulating materials. The second partition (glazed configuration), of the same total height (1.3 meters), includes a 20-centimeter glass panel at its upper section. Finally, the third partition (low configuration) has the same characteristics as the first one, but with a reduced height of 1.1 meters, which is below the average eye level of a seated person.

To recreate an open-plan office environment, four workstations were installed in a semi-anechoic chamber, separated by one of the three partitions under study. The four desks were arranged in a square, as shown in Figure 1. Two participants took part in the experiment simultaneously, seated at workstations 1 and 2, which were positioned diagonally from each other. Speech noise was played alternately through two loudspeakers placed at the two unoccupied workstations, while an omnidirectional source, installed 3.5 meters above the center of the four desks, emitted broadband noise.

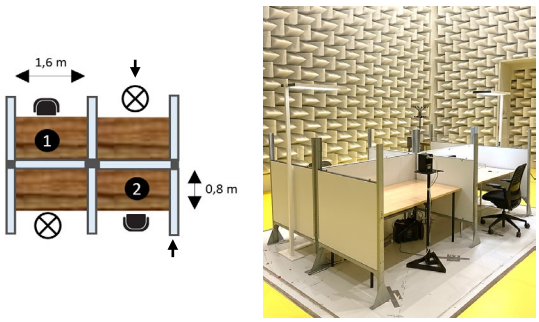

Figure 1: Experimental set-up

Audio stimuli

During the experiment, in each partition configuration, participants were exposed to different auditory stimulus combining broadband background noise and a speech signal corresponding to normal effort (59 dB(A) at 1 meter), in accordance with the study by Monson et al. (2012) [3]).

A background noise level of 49 dB(A) was selected to reflect realistic field conditions. Although this value slightly exceeds the 48 dB(A) ambient noise limit set by the NF ISO 22955 (2021) [4] standard, it allows the STI index (calculated in accordance with standard NF EN IEC 60268-16 (2020) [5]) to be maintained within a range where the intelligibility rate (in %) of sentences increases rapidly.

The STI values for the two workstations for each of the three partition configurations, when the speech noise originates from the workstation at the front and from the one at the side, are presented in Table 1. Speech intelligibility is therefore best with low partitions. It is poorer with glass partitions and even poorer with high partitions.

Table 1: STI values between the two workstations for the three configurations

Configuration	**High**				**Glazed**				**Low**			
Workstation	**1**		**2**		**1**		**2**		**1**		**2**	
Source location	**Front**	**Side**	**Front**	**Side**	**Front**	**Side**	**Front**	**Side**	**Front**	**Side**	**Front**	**Side**
STI	0.48	0.32	0.46	0.33	0.54	0.39	0.54	0.39	0.72	0.45	0.68	0.40

Experimental design

Cognitive task

In order to place the participants in working conditions, they were asked to produce a press review. More specifically, they were required to read press articles very carefully. For each experimental condition, the press review consisted of three themes, each grouping several articles (approximately 10 pages). In total, each participant dealt with nine themes (three per sound condition). For each press review, participants were instructed to take as many notes as possible in order to answer multiple-choice questions (MCQs) at the end of the session.

Questionnaires

The main aim of the MCQs was to encourage the participants to read and remember as many articles from the press reviews as possible. In addition, a performance score was calculated for each condition. In addition to performance, questionnaires were used to assess the subjective effect of the sound and visual environment on the participants. Several dimensions were measured.

Fatigue: Mental and general fatigue were assessed using the Multidimensional Fatigue Inventory (MFI) questionnaire [6].

Mental workload: the cognitive mental workload was estimated with the IWA questionnaire [7] (Individual Workload - Activity) in a laboratory version. This questionnaire evaluates four dimensions of mental workload generated by the activity: intrinsic workload, external workload, available resources and germane workload.

Environment perception: An overall assessment of satisfaction with the environment was conducted. In addition, the sound environment was evaluated, according to four dimensions: noisy, annoying, tiring, and the level of satisfaction with sound privacy. The visual environment was also evaluated, according to three dimensions: annoying, tiring and the level of satisfaction with visual privacy. Responses are assessed on an 8-point Likert scale. For example, responses regarding overall satisfaction range from 1 ("not at all satisfactory") to 8 ("completely satisfactory").

Procedure

Thirty-six participants, including 13 men and 23 women, were recruited. All participants had normal hearing (hearing loss < 20 dB HL). They were divided in 18 groups of 2 persons. Each group participated to three half-day sessions at the laboratory, always scheduled either in the morning or in the afternoon.

Statistical analysis

All statistical analyses were repeated measures analyses of variance, the significant level being set at 0.05. Analyses were performed with R.

RESULTS

An initial analysis focused on performance scores. The analysis of variance (ANOVA) did not reveal any significant difference between the different partitions. An ANOVA was also performed on the subjective dimensions: fatigue, mental workload, and environmental perception. The results did not show any significant difference between the three partition configurations with regard to fatigue and mental workload. However, the overall perception of the environment—both in terms of sound and visual aspects—was preferred for the high and semi-glazed partitions compared to the low partitions. For example, the ANOVA revealed a significant difference between high and low partitions regarding overall environmental satisfaction, based on post-hoc comparisons adjusted using Tukey's method ($p = 0.026$). Mean values are shown in Figure 2. Finally, the analyses highlighted a significant difference between the high and semi-glazed partitions only with respect to satisfaction related to visual privacy ($p < 0.001$).

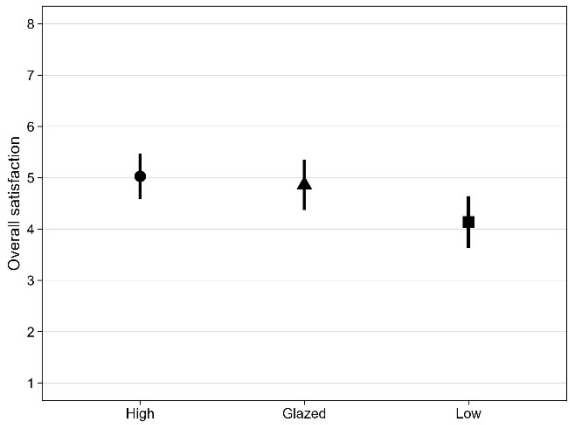

Figure 2: Overall environmental satisfaction assessment for the three configurations (averaged values and adjusted 95% confidence intervals according to the Morey method *[8]*)

CONCLUSION

The three partition configurations did not show any significant differences in performance, fatigue and mental workload. However, perceptions of the acoustic and visual environment were preferred in the high and glazed partition configurations compared to the low partition configuration across several dimensions, including annoyance, tiredness, environmental satisfaction, and privacy. No significant difference was observed between the high and glazed partitions except for visual privacy.

This study suggests that, in the specific case of open-plan offices where the work task requires individual concentration, the use of low partitions may be discouraged due to their negative impact on the acoustic and visual environment. A second experiment will soon be conducted to assess whether access to an external view enables glazed partitions to provide higher workspace satisfaction than high partitions.

Acknowledgements

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Office noise distraction– Psychoacoustic model based on simple sound level metrics

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ABSTRACT

Noise is one of the most distracting environmental factors in open-plan offices. Many kinds of professionals need to assess the noise conditions (e.g., occupational health, facility management, acousticians, ergonomists). However, there is no objective method to assess the distraction caused by office noise. The purpose was to study whether the distraction due to office noise could be objectively predicted using standard sound level data. We conducted three psychoacoustic experiments, where participants rated the distraction of several office noise scenarios. Scenarios had very large variation in overall sound level (40–60 dB L_{Aeq}), number of simultaneous speakers (0–12), and signal-to-noise ratio of speech (-5 … +25 dB). Mathematical optimization revealed a model, where the subjective distraction could be predicted using three measured variables: L_{Aeq} and L_{A5}-L_{A95} with very good agreement. This method can be easily applied in the objective assessment of noise distraction in offices, since the three variables are available in standard sound level meters.

INTRODUCTION

Colleagues' irrelevant speech is the most usual noise source in offices. Because the levels, numbers of simultaneous speakers, signal-to-noise ratios, vary with time and position, the objective measurement of the annoyance elicited by office noise is not a straightforward task. Although the nature of office noise has been the same over decades, there have not been any scientific breakthroughs which would advise how office noise should be objectively measured so that the outcome would predict the noise annoyance experienced by a working person.

Speech Transmission Index (STI) is an objective quantity (value range 0.00–1.00) of assessing the subjective speech intelligibility from speaker to listener. STI is measured in an open-plan office according to ISO 3382-3. It is determined by placing a sound source (producing specific test signal) to the speaker's position and microphone to the listener's position.

Unnecessary speech is known to significantly impair work performance if STI > 0.50 [1]. Therefore, according to Finnish building regulations [2], the room acoustics of open-plan offices must be implemented in such a way that speech intelligibility is minimized (STI < 0.50).

The original reason for developing STI was to objectively assess the quality of speech in electronic systems and rooms. Therefore, STI is limited to a single target speaker and steady-state masking sound situation. STI cannot be used to assess real office sound environments, where the number of simultaneous speakers varies arbitrarily and the target speaker (noise source) is one of them.

Sound scenario in a specific position in the office changes all the time, because the occupancy and number of simultaneous speakers (and their distances to listener and speech efforts) vary. According to the review of Yadav et al. [3], sound levels have varied significantly (39–73 dB) between open-plan offices.

When noise complaints are made in an office, a professional should objectively assess the situation. However, there is no generally accepted method for such assessment.

The distraction caused by a specific sound increases as the equivalent A-weighted sound pressure level (SPL), L_{Aeq}, increases. However, if the sound is speech, distraction does not depend on L_{Aeq} only. There is evidence that even a quiet speech (L_{Aeq}<35 dB) impairs work performance and elevates distraction if the speech is intelligible [4].

Some studies which have proposed that the variability of sound level would play a role in distraction [5–7]. However, these studies are based on single speaker scenarios.

The aim was to develop an objective prediction model that can be used to objectively assess the distraction caused by office noise. The work is completely reported in Ref. [8].

MATERIALS AND METHODS

The model is based on three independent psychoacoustic experiments (pilot, main, and validation), where the participants rated a large range of office noise scenarios. This paper focuses on the main experiment.

Thirty-nine Finnish speaking participants attended in the experiment conducted in TUAS psychophysics laboratory. During the experiment, the participants were advised to imagine a working situation by these words: "*When the sound is playing, imagine that you are doing independent work that requires concentration and thinking, for example in an open office or a library. The sounds are not related to the work you are doing*." Distraction was measured by: "*How much sound would distract your working*?" Eleven-point numeric rating scale was applied where the extreme options were verbally labeled (0 Not at all, 10 Extremely much). Each sound was played for about 10 seconds before the rating was made.

The total number of sound stimuli was 111. Three of them contained only masking at three overall levels 40, 50, and 60 dB L_{Aeq}. The rest (108) contained both speech and masking. The spectral shape of speech and masking conformed with the standard-effort speech of ISO 3382-3. The 108 sounds were formed of 36 core sounds (Fig. 1), which were presented and three overall levels, 40, 50, and 60 dB. Speech consisted of Finnish sentences taken from an audiobook. The sentence order of the book was randomized so that there was no plot to follow. In multi-speaker conditions, the starting moments of sentences were stirred so that the sound scenario was natural babble. When the number of simultaneous speakers increased, the level of masking sound was reduced to keep the fixed overall level.

The sounds were played via headphones. Desired levels and spectra were measured using in-ear microphones of a head-and-torso simulator and by placing the headphones on the torso. For each sound, the L_{Aeq} and sound level variability, $V=L_{A5} – L_{A95}$, were measured to be used as the input variable of the prediction model.

Table 1: Properties of the 37 core sounds. SNR is the signal-to-noise ratio of speech (level difference between speech and masking sound).

Number of speakers	SNR				
	–∞	-5	+5	+10	+25
1		x	x	x	x
1		x	x	x	x
1		x	x	x	x
2		x	x	x	x
2		x	x	x	x
2		x	x	x	x
3		x	x	x	x
6		x	x	x	x
12		x	x	x	x
0	x				

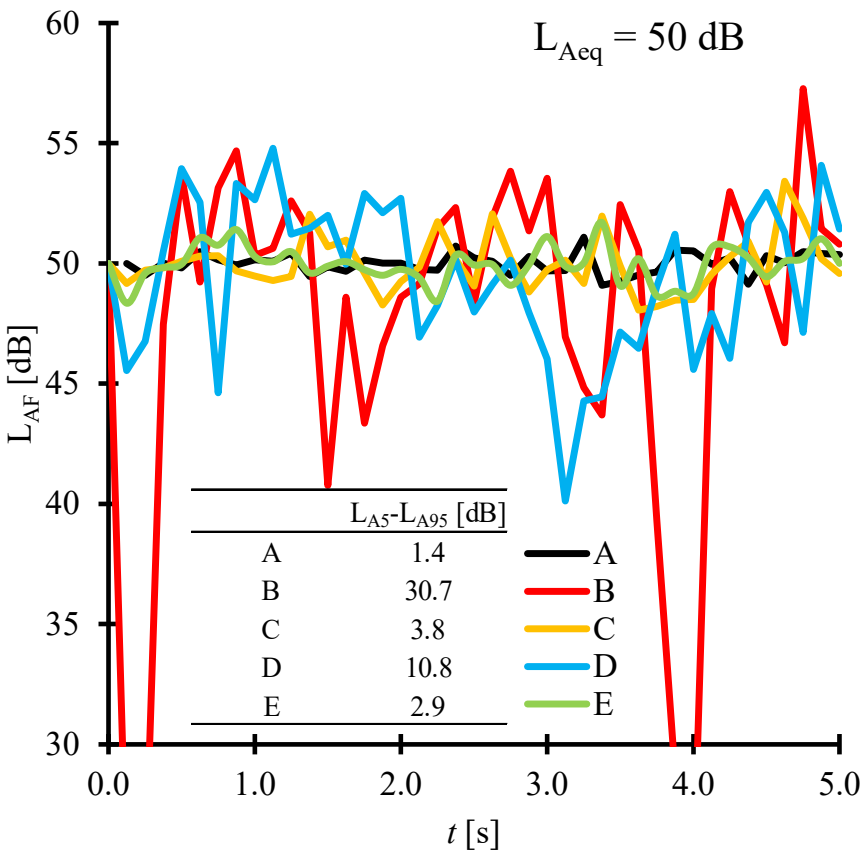

Figure 1: Examples of the sound level profiles for 5 extremely different experimental sounds out of 111. A) Zero speakers, just masking. B) One speaker with SNR=+25 dB). C) One speaker with SNR=-5 dB. D) Six speakers with SNR=+25 dB. E) Six speakers with SNR=-5 dB.

RESULTS

The means of the subjective distractions reported by 39 participants are shown by symbols in Figure 2. Distraction was clearly higher when the sound level L_{Aeq} was higher (different colors). However, distraction varied significantly within each L_{Aeq}. The dependence of distraction on SLV at each three L_{Aeq} levels followed quite similar shape.

At a fixed SNR and L_{Aeq}, distraction increased with reducing (positive) number of simultaneous speakers. Single-speaker or dual-speaker condition was usually the most distracting and zero speaker condition the least distracting. However, we did not base the model on the number of simultaneous speakers, because a sound level meter cannot count them in practical measurements. Instead, we used mathematical reasoning to identify a function that fits the functional dependence of distraction on L_{Aeq} and -V. Microsoft Excel Solver was used to find the constants of this function. The outcoming prediction model got the form

$$D_{pre} = 0.205 \cdot L_{Aeq} - 10 + 8.63 \cdot \frac{V_{15}}{V_{15} + 4.65}$$

where V_{15} [dB] is the minimum of measured SLV (L_{A5} - L_{A95}) and +15 dB. The predicted values are shown in Figure 2 with lines. The predicted distraction agreed well with subjective distraction. The linear association between predicted and observed distraction is also shown in Figure 2. The correlation coefficient was surprisingly large.

DISCUSSION

The model of the Equation means that distraction depends both on sound level and sound level variability. The model was partially supported by previous studies [5–7]. However, they were limited to a single-speaker condition. This study is based on data involving 0–12 simultaneous speakers and very wide range of signal-to-noise ratios (-5 … +25 dB) and overall sound levels (40–60 dB). Therefore, this work provides very strong evidence about the mechanisms under perceived distraction under noise consisting of speech and steady-state background noise.

The full study of Ref. [8] involved three independent experiments, which all investigated the same phenomenon but using slightly different set of sound scenarios and different participants. Experiments 1 (N=10) and 2 (N=39) involved only Finnish participants. Experiment 3 (N=42) was conducted at the BNAM2024 noise congress (Hanasaari hotel, Helsinki, Finland). It involved a group of 30 Finnish speaking participants and another group of 12 participants who did not understand Finnish. The results were very similar in both groups. This suggests that the subjective distraction due to unnecessary background speech might not strongly depend on the understanding of the speech content. Human brains seem to pay constant attention to speech irrespective of its language.

The prediction model of the Equation provides a possibility to objectively predict distraction in workplaces where irrelevant speech is the most usual source of distraction. The model can be easily integrated to standard sound level meters, because the input variables are already available in most of them.

The ability to objectively assess distraction is useful for several kinds of professionals: occupational health physicians and nurses, rehabilitation instructors for the hearing impaired, occupational health and safety officers, occupational hygienists, workplace ergonomists, workplace designers, acoustic designers, and noise measurement professionals.

The model may also be interesting among developers of office space management interfaces. The model allows us to indicate areas or seats in the office layout where noise distraction potential is low or high.

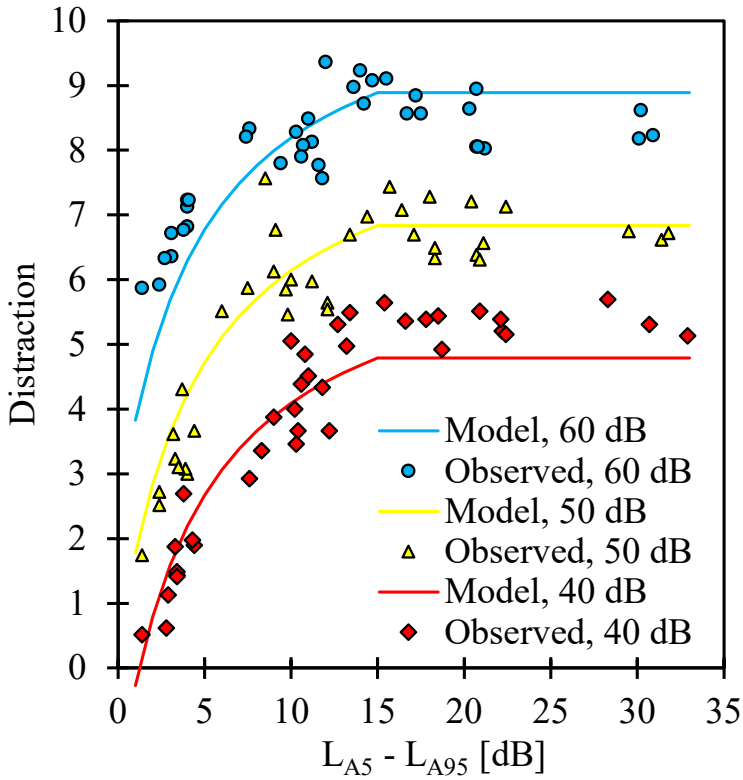

Figure 2: Left) Dependence of distraction on sound level variability (L_{A5} – L_{A95}) and overall sound level, L_{Aeq}. The symbols represent the mean of 39 participants lines represent the prediction of Eq. (1).

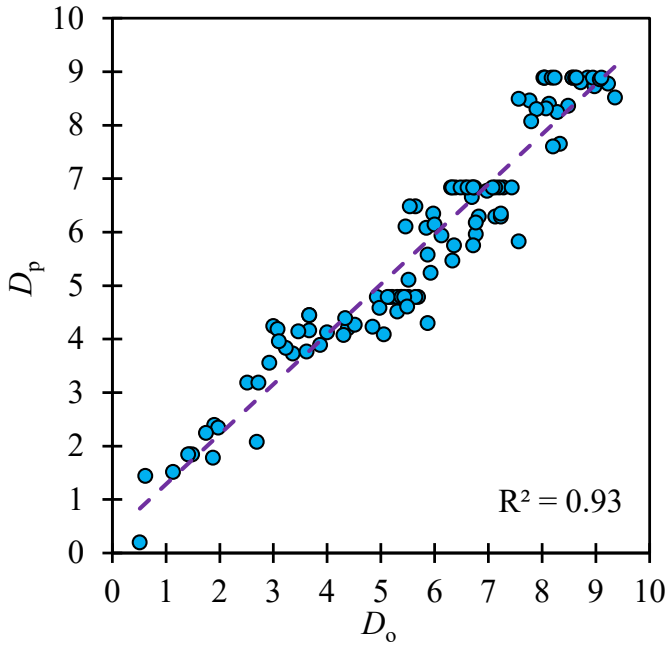

Figure 3: Association between the subjective, D_o, and predicted, D_p, distraction among the 111 test sounds. Prediction was based on Eq. (1).

Acknowledgements

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Sounds and Noises in the Classroom: Perspectives from Children with Sensory Needs in the UK

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ABSTRACT

Several mechanisms have been proposed to understand the impact of unwanted sounds on children's performance and behaviour in the classroom: arousal, stress, control and predictability, executive functions, social attribution, and interference with the processes involved in the learning task. There is, however, a lack of studies involving children with special needs and testing whether these theories can be applied to understand their own experience of the classroom environment. In this study, 23 children with sensory needs, aged 7-10 and attending UK mainstreams classrooms were interviewed. Framework analysis was used to synthesise how classroom noise influences their classroom experience at a social, emotional, cognitive and behavioural level. Children's interpretation of social situations was underlying their emotional responses to noise, showing the need to ask for their perspective directly. At a cognitive level, their responses hinted towards executive function mechanisms, with noise interfering with attentional and working memory processes. At a behavioural level, the extent to which children have a choice over their seating position in the classroom can influence whether they can self-regulate their exposure to noise. Methodologically speaking, this study shows that children reported their sensory experience in a consistent and coherent way, encouraging future research in this area.

INTRODUCTION

Sounds levels in the playground can equal those of a rock concert (110dB, [1]). ICBEN defines noise as a sound that is: (1) harmful due to its intensity and/or (2) unwanted [2]. Harmful sounds exceeding 85dB (the estimated threshold for adult noise-induced hearing loss [3]) have been reported outside of school buildings [4-5] and in active areas such as the gymnasium [6]. Unwanted sounds are likely to occur during a diversity of learning activities in the classroom. They may be overheard conversations, sounds from educational materials, doors, furniture. A sound can be characterised as unwanted based on children's emotional, social and behavioural responses to it.

Emotional responses are typically explored in studies asking participants to report how they feel in the presence of specific sound sources. Questions cover the feelings of being disturbed,

irritated, sensitive, annoyed [7-8]. Judgements about the sound sources (e.g. whether they are responsible, and/or intruding on someone's privacy), perceived control and potential dangers associated with a sound may also play a role [9-12]. Arousal and stress response have been measured in young children [13-14], showing that noise may have underlying physiological effects. These may influence emotional responses.

Cognitive responses to noise have been studied in experimental as well as self-report studies. Here, we would consider as "cognitive" the responses that influence how children process information to complete their learning task. It involves thinking, conceptualisation, memory, representation, mental imagery, attention, reasoning and decision-making [15]. Background sounds can, first of all, overlap with the "target signal", that is to say, what children are expected to listen to: the teacher talking, or another child sharing their ideas. The capacity to process speech in noise involves the efficient allocation of attentional resources [16]. It also requires children to reconstruct degraded phonological information – in other words, they need to "fill the gap" if they only hear some words, or part of the words. Attentional resources and phonological skills develop until adulthood [17-20], and children may need to make extra efforts to process speech in noise. Even if children manage to understand speech in the presence of competing sounds (e.g. listening to instructions with background chatter), it may use cognitive resources that are therefore not available for them to perform the task (e.g. actually thinking about what the teacher said) [21].

When children are engaged in homework (without needing to listen to verbal communication), they are also likely relying on their executive function skills. These enable them to pay attention to the material, juggle with the different pieces of information in their working memory, plan their task, make decisions [17]. Unwanted sounds can interfere with such processes, by: grabbing children's attention; requiring them to process extra verbal information in working memory, disrupting the sequential processing of a task and/or asking them to switch between a task and the surrounding sounds [16], [22-24]. Links between task performance in the presence of background sounds and executive function processes are, however, not systematic [25].

It is also worth keeping in mind that some sounds can have positive impacts on attentional skills. Natural sounds and music may be restorative [26]. White noise has been shown to have positive effects on children with Attention Deficit Hyperactivity Disorder [25], [27]. This may be due to: (1) its even frequency distribution covering up other more unpredictable sounds in the environment; (2) increased arousal of the nervous system which may create an optimal amount of stimulation to focus on a task.

Ultimately, behavioural responses such as approach and avoidance behaviour can give an indication of whether the sound is unwanted. Behavioural responses are particularly visible to teachers and parents, who can document them during classroom observations, or using standardised questionnaires such as the Sensory Profile 2 [28]. These cover visible responses such as "reacting strongly", avoidance responses, visible struggles to engage with learning tasks or, on the contrary, lack of response to input (does not seem to notice it) [28-29].

Overall, several mechanisms have been proposed to understand the impact of unwanted sounds on children's performance and behaviour in the classroom: (1) Arousal; (2) Stress; (3) Control and predictability; (4) Executive functions; (5) Social attribution; (6) Interference with the processes involved in the learning task, in particular the processing of order and phonological information. More work needs to be done to ascertain the explanatory power of these theories.

Previous research has rarely provided a unified approach, studying emotional, cognitive and behavioural responses to classroom noise with the same sample. In addition, more research

needs to be conducted with children with special educational needs [25], [30-33]. Research with children with special needs would help validate theories and mechanisms underlying responses to noise, by testing if they can be applied to understand their experiences.

This study takes place in the United Kingdom (UK). In the UK, governmental guidance to support children with Special Educational Needs and Disabilities (SEND) is published in the 2015 SEND Code of Practice [34]. A child is considered as having special needs if "they have a learning difficulty or disability which calls for special educational provision" (p. 15). Provision is deemed "special" if it differs from what is "generally" provided to children of the same age, and/or if children's needs prevent them from making use of the facilities. This definition grounds special needs in predefined norms and a contextual environment which may or may not match the way children express their abilities [35]. Sensory needs are one of the four areas of needs defined in the Code of Practice. They may overlap with a specific diagnosis, such as autism or ADHD, but may also occur on their own [34]. The UK Government has recently emphasised that support for children should not depend on a clinical diagnosis [36]. The goal of the UK Government is to prioritise the inclusion of SEND children in mainstream settings, where they learn with their peers who may not have special needs (unless families prefer otherwise [36]). Therefore, in this political context, it is fundamental to understand the experience of children with sensory needs in mainstream classrooms.

Research Questions

(1) How do children identified as having sensory needs describe the emotional, cognitive and behavioural impact of classroom noise?

(2) How do these children regulate their exposure to classroom noise?

METHODS

The methodology was co-designed with three local schools in Southeast England [37].

Participants

The study involved twenty-three children in Years 3 to 5 (corresponding to ages 7-10 in the UK; 12 males), identified by their Special Educational Needs Coordinators as having sensory needs. This age range was chosen because children are expected to have developed their spoken language skills, which enables them to discuss their learning and adapt their language to a diverse audience [38]. The sample size was justified by the intention of including children with a diversity of profiles (Table 1), considering both the potential for themes to recur across interviews and to contain information depth/power [39]. In line with the governmental definition of special needs, children with or without co-occurring diagnoses were including, making the sampling strategy a needs-based, transdiagnostic one [40-41].

Table 1: Study Participants

Year group	Profile as Reported by Special Educational Needs Coordinator
3	SEN support
3	SEN support
3	SEN support
3	SEN support
3	SEN support

3	Close monitoring by SENCO for sensory needs but not on formal SEN support
3	ASD diagnosis
4	No diagnosis - undergoing assessment for ADHD
4	SEN support - has been through assessment but didn't meet criteria for diagnosis;
4	SEN support
4	Sensory needs - Working diagnosis with potential ASD and ADHD
4	ASD diagnosis; EHCP
4	SEN support and waiting for diagnosis
4	Close monitoring by SENCO for sensory needs but not on formal SEN support
5	SEN support
5	ASD diagnosis
5	SEN support
5	EHCP and inclusion centre; ASD diagnosis
5	SEN support; ASD diagnosis
5	ASD diagnosis; ADHD diagnosis
5	SEN support
5	SEN support
5	SEN support

Note. ASD: Autism Spectrum Disorder; ADHD: Attention Deficit Hyperactivity Disorder. EHCP: Education, Health and Care Plan – legally binding document for families to outline required support in school. Participants' gender is not reported individually to preserve anonymity.

Procedure

Children were interviewed individually, in a quiet room in their school, for 30-60 minutes. The interviewee first sought verbal assent, and explained the ground rules (Box 1).

Box 1. Ground rules

- You can say "pass" if you don't want to answer.
- Take time to think before you answer.
- Tell me if I don't understand you, or if you don't understand me.
- There are no right or wrong answers; say what you want.
- We can take a break at any time for that, simply show me this card [clock card]
- If you would like to stop and go back to class, show me this card [stop card]
- You can choose any name for this interview. What do you want your name to be?

Measures

In order to give children's flexibility to express their preferences in their own words, a semi-structured narrative, play-based interviewing technique was used [42-43]. The interview schedule was based on seven senses [44-45]. Open questions were first used for each sense to avoid suggesting a particular answer. The interviewee refrained from providing cues, suggestions or guidance [46]. Prompts and play material (e.g. photos of the classroom, pens and pencils) were available. Consideration was taken of the subjective nature, verbal and non-verbal abilities of children [47]. For example, if a child did not understand certain words or phrases, the researcher offered alternate expressions. Open questions were followed with

close-ended questions to: (1) wrap up each section on a specific sense; (2) check that a child's answer was consistent and coherent; (3) ensure that a child's response resisted contradiction [48]. Examples of questions are provided in Box 2. This paper focuses on reporting results pertaining to auditory stimulation.

Box 2. Sample of Questions from the Interview Schedule

Ice-Breaking question:
• What is your favourite thing to learn about?

General questions about the classroom
Let's talk about your current classroom. [Show a photo of their classroom]
• What do you like about your classroom? Why?
• What do you dislike about your classroom? Why?
• Where would you choose to sit? [Ask the child to show on the photo by placing a sticker where they would like to sit] Why? [Ask them to show you in relation to the photo and prompt discussion whether close to radiator/door/window]

Questions about auditory stimulation
• What noises can you hear in your classroom? Where are they coming from? From inside of the classroom or outside?
• What noises do you like to hear in your classroom? Why?
• What noises do you not like to hear in your classroom? Why?
• Do you find concentrating harder when there are lots of people talking in your classroom? Why or why not?

Ethics

The study was approved by the Faculty Ethics committee of the University of Portsmouth (reference number: FHSS 2023-058) on November 2023 (with amendment on 8th May 2024), in compliance with the Declaration of Helsinki, the Concordat to Support Research Integrity (University UK, 2019) and the UK Research Integrity Office (2023) Code of Practice for Research. Informed written consent was provided by the headteachers and SENCOs of the participating schools, as well as children's guardian. Written consent included the permission for the anonymised results of the study to be published. Children gave their verbal assent to participate. Continuous assent was ensured by having a clock, and a stop symbol on the table, for children to indicate their desire to pause or stop the interview. The interviewers also continuously monitored nonverbal signs of engagement.

ANALYSES

Data was analysed on NVivo R1.7 using qualitative Framework Analysis [49]. This technique enabled a systematic, thematic analysis of the data, while charting themes across the sample and for each participant, to map out individual differences. The analytical steps (Table 2) followed a constructivist approach [50].

Table 2. Analytical Steps

1	**Familiarisation** A case node was created for each participant, including their transcript and anonymised demographic information (gender, school year, special needs status). Two researchers from the team independently coded two transcripts, before comparing their codes and annotations. The process was open, not hierarchical, using "free nodes". Codes organised participants' ideas into units of meaning. The goal was to apprehend the data in a more concise format, considering both the participants' perspectives and the researchers' interests.
2	**Identifying a Thematic Framework** Open coding was applied to all transcripts by the first author, with meetings being held with the team to cross validate the codes. Segments of data corresponding to a particular code were critically analysed to ensure that they were representing a consistent, informative unit of meaning with a specific, non-redundant rule for inclusion. Codes were organised into a hierarchical structure (a "tree") that more closely related to the research questions.
3	**Indexing** The application of this hierarchical framework to each interview was systematically reviewed. A summary was written for each code and their name chosen. Decisions were made based on the links between the code, theoretical frameworks and social implications.
4	**Charting** A short summary was written for each sensory modality and participant.
5	**Mapping and Interpretation** This phase provided an integrated view of children's perspectives (see Figure 1).

RESULTS

This section reports the indexing and mapping process. Charting is available upon request.

Identification of Noise. Noise coming from outside included birds (n=2), a fox scare (n=1) and transportation noise (n=4; "motor bikes", "cars", "like when trains went past"). Natural elements were also perceived, such as the rain, wind, trees swaying (n=7). Indoor noises included doors being shut (n=2), and equipment such as the smartboard and educational material (n=7; "the computer tapping", "the smartboard"). Noise generated by people (in class, in the playground or canteen) dominated (n=22) and formed part of the usual auditory landscape: "Basically, all the stuff that would make a classroom a classroom.". As reported by five pupils, some teachers played background noise such as white noise or calming music.

Physical Features of the Noise. One child commented on the fox scare being very high-pitched. Reverberation was disliked by one child, who commented on the high ceiling which created an echo in the classroom. Loudness was by far the most common attribute that was associated with annoyance and frustration (n=19). One child described it as a "tsunami of noise". Paradoxically, sudden changes in noise levels, including when the classroom was becoming very quiet were disliked by two children: "So sometimes it affects me whenever like they're like constantly doing it [screaming], but when it's just like, ohh and then it stops for one point then I'm like alright, I was used to the screaming". Sudden changes in noise levels can also represent change from normality: "Because if it's too silent it's just like why is it silent, it's not normal for me to be that quiet".

Physiological Responses to Noise included regulating energy levels, by feeling calm after hearing teacher's relaxing music or the rain (n=4) or, on the contrary, embracing an energetic atmosphere: ("[When do you like it not to be silent?] When I'm feeling energetic."). Headaches (n=2) were a negative physiological effect of noise and so was nausea (n=1), which was related to the noise made when sweaty hands got onto the whiteboard. Ear pain was described by three children in association with loud noise. Paradoxically, silence created the condition for one child to feel ear pain, which could be tinnitus: "I don't like it completely silent because it makes my ears go like a funny sound".

Social Dynamics. Whether loud noises were perceived as annoying or not depending on their social valence, and whether they represented conflictual (e.g. shouting), or joyful interactions (e.g. playing) (n=10): "Sometimes it can be a bit loud, cause everyone's just chatting sometimes, although that that does make me feel like there's some like spirit in the club." When noise originated from verbal interactions, a lack of social acceptance seemed to underlie children's negative responses. In other words, it was not background talk itself which was problematic, but the difficulty in social harmony that it represented: "But we've got some really annoying people that always talk. […] Like when I try to talk to them, they like cover their ears when I'm trying to talk to them. […] but then they're like fluently talking with everyone else. I'm confused."

Cognitive Response

Twenty-two children commented on the impact noise had on their learning. The main negative impact was lack of focus: "It's because like when they're shouting, they're like, attracts me."; "Instead of focusing on my work, I'm focusing on trying to understand what they're saying." Links to subvocal rehearsal and working memory could be made here: "I can't even hear myself think." In addition, noise might come with extra effort and time needed to be spent on tasks: "[What about if your classroom is completely silent?]. I work a lot easier and little faster than before." For some children, complete silence is uncomfortable and low levels of white noise or calming music are preferred.

Whether background noise interfered with the task at hand was relevant to children. Children's ability to hear the teacher as the relevant "signal" and therefore to follow instructions was commented upon. In addition, being seated near the teacher, and receiving one-to-one support, was perceived as supportive of learning. Background conversations were acceptable when children helped each other with their homework: "Sometimes people wanna whisper like a good word if they, if there's someone stuck on something."; "Why wouldn't you like if it was silent all the time? Cause then, […] we wouldn't even be able to talk about things like our work."

Behavioural Regulation of Auditory Input

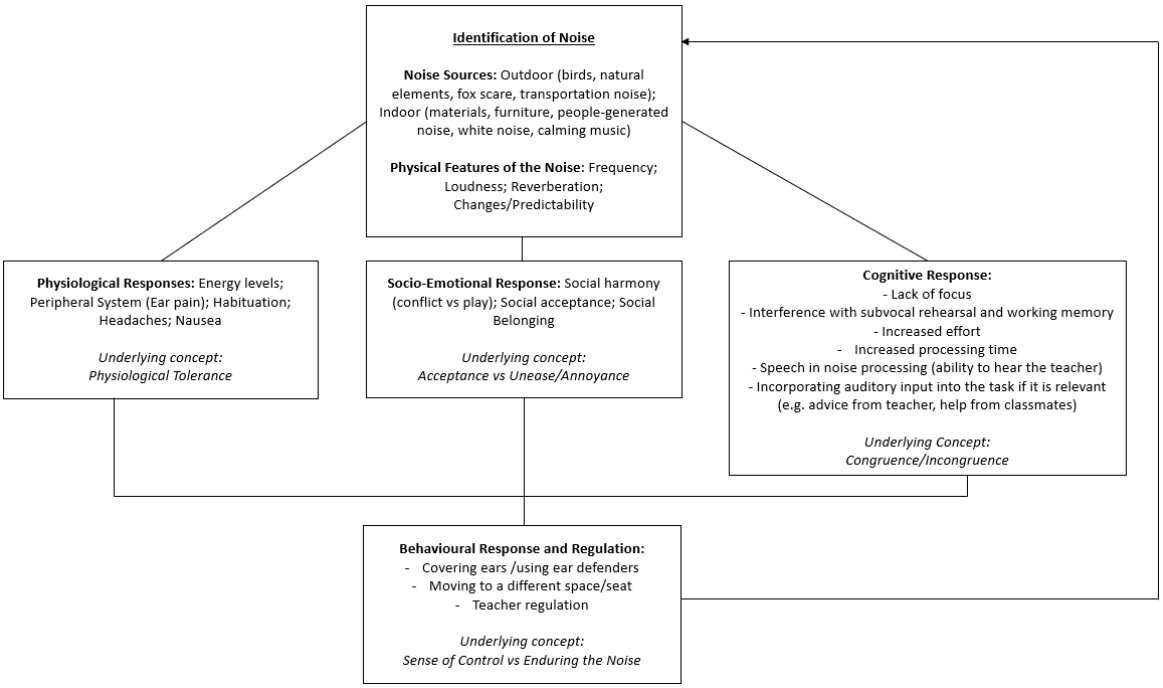
Blocking Noise from Entering the Peripheral System, when it had to be endured, was a short-term response for two children who would cover their ears: "I go [cover their ears]". One child reported using ear defenders.

Teacher Regulation was mentioned by four children. This included interjections, loss of break time when the class was too noisy, and choosing where children were seated. Some children proactively sought teacher support in regulating noise levels: "If it's too noisy, I'll just tell a teacher."

Moving to a Different Space was a strategy for six children to regulate auditory input, either by moving table or leaving the room altogether. This could take the form of behavioural dysregulation: "it would be so loud I would just want to go outside, slam the door shut then go in the hall".

Noise Influences Seating Preferences for ten children. Their choice of where they would like to sit reflected whether they wanted to engage in classroom chatter or moving away from it: “[Why would you sit there?] Because there's someone who's calm and you know.” It also meant, for some children, being seated away from the door when noise was coming from the corridor or the alarm bell. Noise levels from the smartboard was considered: although it might be considered relevant for learning, some children have their own preferences: “I like sitting at the back because it's like […] more quiet if there's a video on.”

Figure 1: Thematic map representing children’s responses to classroom noise



DISCUSSION

This study investigated how children identified as having sensory needs describe the emotional, cognitive and behavioural impact of classroom noise. It also explores how these children regulate their exposure to classroom noise

The types of noise(s) identified by children with sensory needs corresponds to what has been reported in studies in UK mainstream schools [51] and international review papers [3]. Other people were the most common source of noise, again matching previously published international research [11-12], [52]. Although loudness, speech-to-noise ratio and reverberation times are physical characteristics of sounds that are often considered in research and policy regulation [53], children mainly spoke about loudness and fluctuations. What made these sounds “noises” could be understood based on children’s physiological, social, cognitive and behavioural responses to them.

On a physiological level, some children reported responses from the peripheral system (ear pain, tinnitus). These responses were not found across the whole sample and may vary based on individual differences (comfortable hearing threshold, individual sensitivity), and sudden peaks in loudness noticed in the classroom. Children commented on how noise interacted with their energy levels which can possibly be understood in terms of arousal, and the balance between what is felt inside and what is perceived outside of the body [54]. When describing the physical characteristics of noise, some children commented on whether the noise was persistent

or, on the contrary, had sudden changes in loudness. Perhaps one aspect to further study here is habituation, which is a biological regulatory mechanism that usually decreases the intensity of a response to a specific sensory input [55-56].

From a social level, children commented on whether conversations represented social harmony, acceptance and belonging or, on the contrary, conflict. In that sense, it is important to understand children's interpretation of a situation. These can differ from adult expectations, as reported in tools such as the Sensory Profile 2 [28]. The social valence of sound stimuli is not usually reported in research with school age children, which tends to characterize speech stimuli in terms of the number of speakers included, and the presence or absence of environmental sounds [33].

On a cognitive level, children's responses hinted towards executive function mechanisms, noise interfering with attentional resources and working memory processes [22]. The masking effects of noise were noticed, such as when unwanted sounds covered the teacher talking. Children judged whether overheard conversations could feed into their learning task.

On a behavioural level, results indicate that children may try to change their seating position, or change space entirely if they are overwhelmed with noise. Flexible seating may afford the opportunity for children to self-regulate their noise exposure [57].

Methodologically speaking, the vast majority of children reported their sensory experience in a consistent way throughout the interview, and resisted contradiction. Children conveyed their experience by sharing specific anecdotes (e.g. a specific instance in which sensory input elicited a particular response) and their internal dialogue (e.g. repeating dialogue that had been running through their head during a specific sensory experience) [58]. Future research may use a larger sample and triangulate results with biological measures (e.g. stress response and skin conductance), experimental performance measures (e.g. cognitive tasks), and multi-informant methods. Interview methods are important because they enable educators and children who do not have sensory needs to understand the perspective of children who do have special needs. Empathy is a two-way street [59-60] and is partly based on embodied responses. Sensory differences between children, and between children and adults can create a different embodied experience of the world and different assumptions about what constitutes a comfortable and successful interaction [61].

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How did employees perceive the addition of sound insulating booths in the office?

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ABSTRACT

Based on numerous surveys worldwide, noise annoyance and a lack of speech privacy are one of the most usual environmental problems in offices. Since 2010, booths have been increasingly used in offices to mitigate these problems. Booths can be placed in almost any desired location without construction work. Furthermore, their sound insulation properties can reach the same level as fixed rooms do. Despite the trend, there is very little independent research on how booths are perceived in the workplace. The goal of our study was to investigate how the addition of booths impacted on employees' perception of an activity-based flexible office. The employees had reported issues with speech privacy in the office; therefore, the addition of booths was a desired change in the workplace. Seven booths were installed in the office (both one-person booths and four-person booths). The employees' experiences were assessed before and after the installation. After the booth installation, the employees' perception of the office was more positive in many areas, such as privacy and other indoor environment factors. After the addition, employees were more satisfied with the office and even job satisfaction was higher. The results indicate that the change in the working environment met the employees' needs. Based on our study, booths can be recommended to offices where employees report about insufficient speech privacy.

INTRODUCTION

One of the most disturbing sounds in open-plan offices is speech [1]. Lack of speech privacy can contribute to the acoustic dissatisfaction in offices [2]. In addition, greater availability of quiet workspaces in open-plan offices has been associated with higher environmental satisfaction [3]. The annoyance caused by speech and the lack of speech privacy could be alleviated by movable and sound-insulated booths, as they would provide spaces for work requiring concentration and for confidential discussions. However, employees' experiences of booths have been studied very little, even though their popularity has been increasing since the 2010s.

The aim of this study was to examine how the introduction of booths affected employees' experiences in an office where dissatisfaction with speech privacy had been expressed.

METHODS

The study was conducted in an activity-based flexible office at the University of Oulu, where only administrative staff worked. The staff (N = 58) carried out tasks including the handling of students' financial and study-related matters online or by telephone. Students did not visit the premises. The work tasks occasionally required complete speech privacy, which, according to the staff, was not properly achieved. All workstations (38 in total) were non-assigned and bookable via a reservation system. Most workstations were in open-plan areas or shared offices. The office had four quiet spaces.

A total of seven booths were installed: four single-person booths and three meeting booths for 2–4 people. With the addition of the booths, some workstations were removed, resulting in 30 workstations in shared spaces and a total of 11 quiet spaces, including the new booths. The office had undergone renovation in 2020. The sound attenuation class of the single-person booths according to ISO 23351-1 was A, while the meeting booths were class B [4]. The booths were enclosed spaces with mechanical ventilation (fan + transfer air openings) and automatic lighting. Approximately half of the interior surfaces were glass, with the remainder sound-absorbing surfaces. The one-person booths were equipped with an adjustable desk and a chair. The meeting booths contained a table and two sofas. All booths were included in the office space booking system in the same way as other workstations.

The surveys were administered three times: before the change (Phase 1) and twice after the change (Phases 2 and 3). The surveys assessed satisfaction with indoor environmental factors, work, and the work environment, as well as perceptions of the availability of the spaces. In the analyses, the impact of the change was examined by comparing Phases 1 and 2. The permanence of the change was examined by comparing Phases 2 and 3. Phase 3 served as a control for the study (there were no exceptional changes in the premises, management, or personnel between Phases 2 and 3).

Satisfaction with indoor environmental factors was assessed using the question "How satisfied are you with the following factors at your workplace?". The evaluated indoor environmental factors and the seven-point scale are shown in Figure 1. Using the same scale, environmental satisfaction was assessed with the question "How satisfied are you with your work environment at your workplace as a whole?". Job satisfaction was assessed by question "How satisfied are you with your job overall?" using a five-point scale from 1 very unsatisfied to 5 very satisfied. The availability of the spaces was examined using statements. The statements and response scale are shown in Figure 2.

The survey results were analysed using RStudio (version 4.3.0) with linear mixed models. The model accounted for repeated responses from the same participants across different Phases.

RESULTS

The questionnaires were completed by 49, 42 and 32 employees in Phases 1–3, respectively. Satisfaction with indoor environmental factors increased between Phases 1 and 2 in terms of speech privacy, visual privacy, temperature, the amount of workspace and storage space, and ease of interaction (Figure 1). Significant changes were not found between Phases 2 and 3.

Perceived adequacy of the spaces improved from Phase 1 to Phase 2 (Figure 2): participants felt that meeting spaces were more easily available, and that it was easier to find a quieter place for working, discussions, and remote meetings.

Overall environmental satisfaction increased slightly over time across the entire study period ($p = 0.012$; means: Phase 1 = 1.2; Phase 2 = 1.4; Phase 3 = 1.7). However, there were no significant differences between Phases 1 and 2 nor between Phases 2 and 3.

Job satisfaction was higher in Phase 2 than in Phase 1 ($p < 0.01$). No differences were observed between Phases 2 and 3.

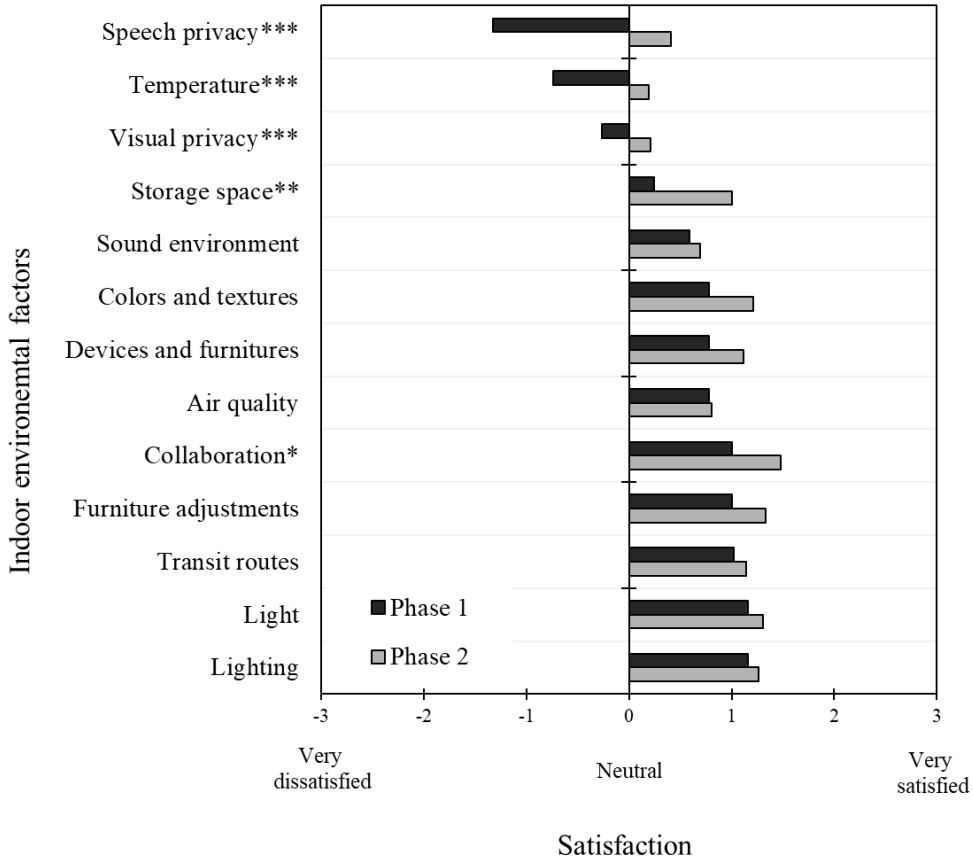

Figure 1. The mean satisfaction with indoor environmental factors in Phases 1 and 2. Asterisks denotes the significant difference between the phases (* $p<0.05$, ** $p<0.01$, and *** $p<0.001$).

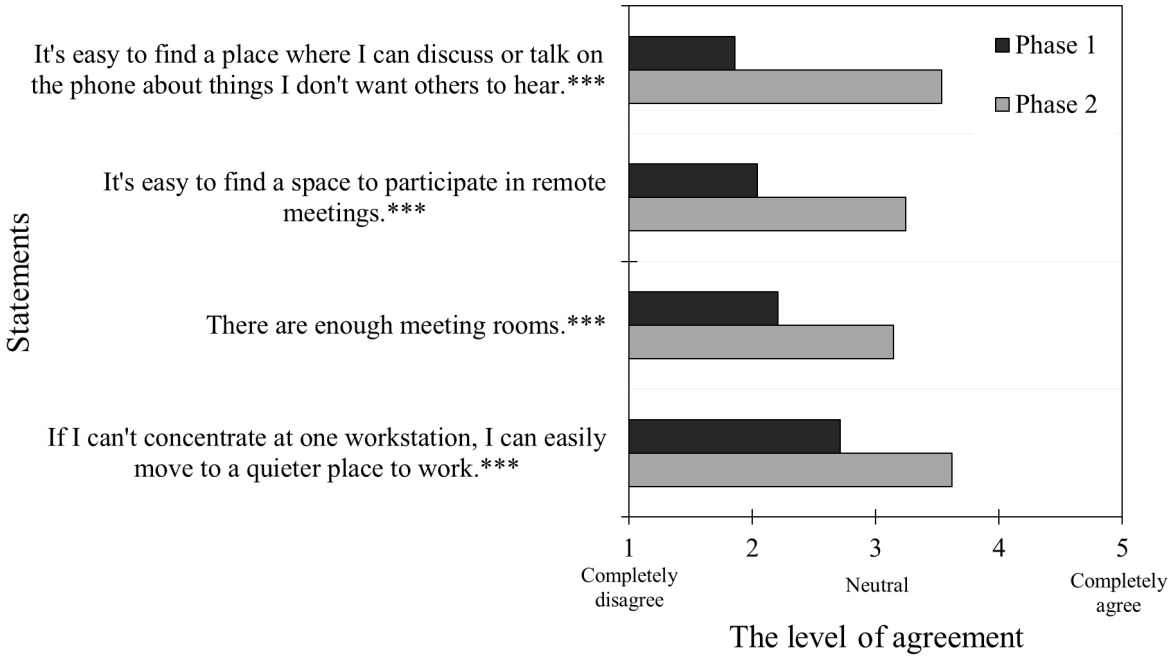

Figure 2. The averages of the statements regarding workspace availability in Phases 1 and 2. Asterisks denote the statistically significant difference between the phases (*** p<0.001).

DISCUSSION & CONCLUSION

By adding booths to an activity-based flexible office, perceptions of the office environment became clearly more positive. The change improved experiences of privacy and the agreement of availability of different types of spaces. Together with other factors, these improvements even increased job satisfaction. However, job satisfaction does not often change because of environmental changes alone. In this study, employees may have felt that they had influence over their own work environment: management listened to employees' wishes regarding improvements to the office. Employees had expressed problems with privacy, and the booths provided a solution to this problem. After the addition of the booths, the work environment supported the performance of work tasks better, which may also explain the improved job satisfaction.

The changes can be considered permanent, as the ratings were nearly equal in Phases 2 and 3. Only satisfaction with temperature was higher in Phase 2, which may have been due to a change in season.

No differences were observed in the sound levels measured in the office before and after the spatial change. This may indicate that even before the change, employees did not speak in the office because they felt it would disturb others and was not possible due to confidential discussions. However, the improved experience of the workspace shows that after the spatial change, staff had more spaces in which to conduct confidential conversations.

Based on the study, booths can be recommended at least for offices where lack of speech privacy is insufficient. In this study, the speech sound attenuation of the booths was high (classes A or B). The results may not be applicable to booths with lower speech sound attenuation. Nevertheless, it is likely that the applicability of our study is relatively broad in the eyes of office environment developers, given the fact that such well-controlled studies on booths are not available in the research literature.

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Age Matters: Developmental differences in children's listening effort across classroom environments - Insights from three studies

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ABSTRACT

Listening in noise is inherently more challenging for children than adults, yet how age influences children's listening effort in realistic classroom environments is still subject to research. Three complementary studies investigated this question using subjective and behavioural measures of listening effort. The first study employed a dual-task paradigm with word recognition and digit recall in an acoustically simulated classroom with multi-talker babble at signal-to-noise ratios of 0 dB and −3 dB, finding that younger children (6–7 years) reported greater subjective and behavioural listening effort than older peers (8–10 years). The second study extended these findings by manipulating task complexity, revealing that younger children (6–7 years) showed slower response times, indicating greater behavioural listening effort than older children (8–10 years). Younger children also reported higher subjective listening effort despite equivalent noise exposure. The third study measured subjective listening effort in real classrooms across activities, demonstrating higher subjective effort in first- than fourth-graders. Collectively, across all three studies, younger children consistently exerted greater subjective and behavioural listening effort than older children in realistic classroom noise. These findings align with recent developmental research and raise a critical question: How can we redesign classroom environments to accommodate age-related differences and support younger children's listening and learning? Implementing age-appropriate acoustic interventions, such as noise reduction strategies, preferential seating, or modified activity structures, may be essential for optimising listening conditions across the primary school years.

INTRODUCTION

Children are more susceptible to noise and reverberation than adults. Not only are children affected differently by noise than adults, but there are also differences among children according to their stage of development. Several studies have found that listening effort is higher in younger children and decreases with development. For example, Oosthuizen et al. (2020) reported this for behavioural listening effort using a single-task paradigm in seven- to twelve-year-olds, and Danneels et al. (2021) found comparable results using a dual-task

paradigm in six- to seven-, eight- to nine-, and ten- to twelve-year-olds. Prodi et al. (2019) explored younger ages with a single-task paradigm, revealing decreasing behavioural listening effort with age, while Prodi and Visentin (2022) confirmed this trend in eleven- to thirteen-year-olds. Overall, a developmental trend of decreasing listening effort with age is observed in children aged five to thirteen.

However, further research is needed to better understand these changes in realistic classroom environments, where children spend considerable time. This paper synthesizes three studies focusing on developmental age effects on children's subjective and behavioural listening effort in simulated and real classrooms. Primary school in Germany typically covers ages six to ten, so two age groups were defined: younger children (six- to seven-year-olds, first- and second-graders) and older children (eight- to ten-year-olds, third- and fourth-graders).

METHODS

Participants

A total of 161 children with normal hearing, aged between six and ten years, participated across three studies. Study one tested 44 children, comprising 22 younger children (first- and second-graders aged six to seven) and 22 older children (third- and fourth-graders aged eight to ten), along with 25 young adults for comparative purposes (Seitz et al., 2024). Study two tested 39 children, with 18 younger children aged six to seven years and 21 older children aged eight to ten years (Seitz & Fels, 2025). Study three recruited 78 children from seven primary school classes, including 40 first-graders aged six to seven years and 38 fourth-graders aged nine to ten years. Participants of studies one and two exhibited normal hearing thresholds of 20 dB HL or better across frequencies from 0.5 to 4 kHz. Participants of study three had normal-hearing according to parent and teacher reporting. Exclusion criteria encompassed hearing or vision impairments as well as ADHD disorder. The participant samples maintained demographic balance, with approximately 50% female representation across groups. Parental informed consent and child assent were obtained for all participants, and the studies received approval from the RWTH Aachen University ethics committee.

Study 1: Dual-Task Paradigm in Simulated Classroom Situations

The first study investigated behavioural listening effort using a dual-task paradigm and subjective listening effort with a newly developed questionnaire (Seitz et al., 2024). It took place within a listening booth and simulated realistic classroom situations. The primary task required participants to recognize phonologically similar monosyllabic words drawn from a word recognition task (Klatte et al., 2010), presented at 60 dB SPL. The secondary task involved visual digit recall. Experimental conditions, presented in five noise blocks of 28 trials each, consisted of quiet, anechoic multi-talker babble at SNRs +0 dB and -3dB, as well as multi-talker babble in a simulated classroom at signal-to-noise ratios (SNRs) of +0 dB and -3dB. Both single-task and dual-task blocks were evaluated for error rates and response times. Subjective effort ratings were collected immediately following each block and consisted of a joint listening effort score built from ratings of well-being, task performance, and effort (Seitz et al., 2024).

Study 2: Effects of Task Complexity on Listening Effort

The second study extended the dual-task paradigm from the first study by incorporating evolved room acoustic simulations and different variations in task complexity (Seitz & Fels, 2025a). Button-press response time was measured during a word recognition task (Klatte et

al., 2010) at sound playback of 60 dB SPL to assess behavioural listening effort. The questionnaire from the first study was used to measure subjective effort. A visual decision task was incorporated to assess distinct levels of task complexity. The acoustic environment replicated the simulated classroom noise from the first study in a more refined virtual classroom, featuring silence and multi-talker babble at an SNR of 0 dB, each in an anechoic and simulated classroom condition.

Study 3: Subjective Listening Effort in Real Classrooms

Field measurements were conducted across seven German primary school classrooms during four distinct classroom activities: silent individual work, teacher-student interaction, group work, and classroom breaks (Seitz & Fels, 2025). Measured acoustic parameters included sound pressure level (SPL), A-weighted SPL, loudness, and sharpness. Further, for each classroom a room acoustic assessment was conducted at the beginning of each school day. Following each activity and at the beginning of the school day, children completed a subjective effort questionnaire (Seitz & Fels, 2025).

RESULTS AND DISCUSSION

Across three studies (Seitz et al., 2024; Seitz & Fels, 2025; Seitz & Fels, 2025a), younger children aged six to seven years demonstrated greater subjective and behavioural listening effort than their older peers aged eight to ten years when exposed to realistic classroom noise environments. This revealed a clear developmental pattern spanning both controlled laboratory settings and in-situ field measurements.

In the simulated classroom conditions of studies one and two, behavioural indicators such as secondary task error rates and word recognition response times showed that younger children experienced heightened cognitive demands during speech processing tasks, particularly when signal-to-noise ratios were adverse and task complexity was increased. These behavioural findings were supported by subjective effort ratings, with younger children reporting greater perceived difficulty in both quiet and noisy conditions.

Study three (Seitz & Fels, 2025) extended this pattern to real classrooms, where acoustic measurements documented poorer listening conditions, characterised by elevated sound pressure levels during group activities and correspondingly higher subjective effort among younger children. This real-world evidence highlights how developmental differences interact with typical classroom acoustics to increase listening difficulties for young primary school pupils.

Taken together, the multidimensional approach employed across the studies shows that improvements in central auditory processing and cognitive resource management that occur with age progressively reduce the effort required for listening between the ages of six and ten. This is consistent with the Framework for Understanding Effortful Listening (Pichora-Fuller et al., 2016).

CONCLUSION

These three studies (Seitz et al., 2024; Seitz & Fels, 2025; Seitz & Fels, 2025a) provide robust evidence that six- to seven-year-old primary school children exert substantially greater listening effort than eight- to ten-year-olds in classroom environments. This establishes age as an important determinant of auditory processing demands during these critical learning years. The developmental difference, whereby listening effort decreases with increasing age, may stem from maturing central auditory and cognitive mechanisms that enhance speech

perception in noise. Such differences have significant implications for educational equity, as high listening effort can hinder comprehension, attention, and academic performance among first- and second-graders. Targeted interventions should therefore be considered, including acoustic designs differentiated by age, such as enhanced signal-to-noise ratios for younger children, strategic seating arrangements, and activity modifications that minimise concurrent noise. Future research should investigate acoustic improvements in schools that reduce cognitive load for children of all ages, but specifically for younger ones.

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The BIBB/BAuA Employment Survey: A large data basis to examine results on the acoustical work environment in relation to other work-related aspects

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ABSTRACT

The BIBB/BAuA Employment Survey is an extensive cross-sectional survey covering a wide range of questions on occupations, education and health aspects (BIBB: Federal Institute for Vocational Education and Training; BAuA: Federal Institute for Occupational Safety and Health). This survey is conducted every six years with around 20,000 employees as respondents. Among the questions on working conditions also the acoustical work environment is considered. The results for these questions can be evaluated in relation to other topics from the wide range of work-related questions in this survey. This has been done in recent years with a view to various aspects, such as the job requirement level, well-being, or sound sources. Some of the results obtained so far were: (1) The percentage of employees working frequently under noise varies clearly with the job requirement level of the particular activity. (2) When employees frequently work in unfavourable acoustic conditions and experience this as a burden, they most often name machines or equipment in their working environment as the main source. (3) Employees who are frequently affected by disturbing sounds are more likely to report certain health complaints, like physical exhaustion or general fatigue and exhaustion, than employees who work less often under disturbing sounds. This contribution summarises the findings to date from the BIBB/BAuA Employment Survey with respect to noise and disturbing sounds in relation to other aspects of this survey. In addition, it will be reported what is currently under analysis and what is planned next.

INTRODUCTION

The BIBB/BAuA Employment Survey is an extensive cross-sectional survey in Germany, with around 20,000 employees as respondents in each wave of the survey. It is carried out every six years in an institutional cooperation by the Federal Institute for Vocational Education and Training (BIBB) and the Federal Institute for Occupational Safety and Health (BAuA). With a total of more than 300 questions the survey covers a wide range of topics related to occupations, education, and health aspects, also including many questions regarding working conditions, which are of particular interest for the BAuA.

The aim of the survey is to provide representative information on the workforce and jobs in Germany for research into occupations and qualifications, as well as for reporting on the world of work. The results of the survey can serve to improve our understanding of working conditions and the associated workload, as well as shed light on the link between the experienced burden and health issues.

The methods and findings from all waves of the survey are published in various publication formats with different focus, like comparisons across the years, summarising many aspects, or concentrating on a subset of a few questions related to a specific topic and linking the results e.g., to a specific research context [1-5]. Among others, there is also a series of BAuA Fact sheets dealing with results of the surveys. Many of these BAuA Fact sheets are also available in English language (e.g. [6; 7]). Information on all waves of the BIBB/BAuA Employment Survey (2006, 2012, 2018, 2024) is available via the BIBB Research Data Centre [8].

Since noise or the sound environment in general are very important issues in the workplace, the survey also includes some questions on the acoustical work environment (for details on these questions see “Methods”). The acoustical work environment is important for two reasons. On one hand noise at high sound pressure levels can cause auditory effects on employees and ultimately lead to a noise induced hearing loss, which is an irreversible damage of hearing ability. On the other hand, noise at high as well as at comparatively low sound pressure levels can cause non-auditory effects, such as effects on well-being, performance, or health issues other than hearing problems. That means, a large number of employees in many different occupations can be affected by an adverse acoustical work environment. According to several studies the acoustical work environment is not only one of many important issues in the work context, but may be the most significant factor (see e.g. [9; 10]). The adverse effects of unwanted sounds at the workplace on cognitive performance are also part of the review of ICBEN Team 4 [11].

Therefore, there are many good reasons to take a closer look at the data collected on noise and disturbing sounds at the workplace during the BIBB/BAuA Employment Surveys. This has been going on for several years with varying focus. The large number of participants allows for an analysis for different subgroups, like, e.g., workers from different occupational fields. The large number of questions provides a broad range of information, that is usually not available in more specific studies on noise effects, e.g., about job requirements.

The results of this large-scale survey therefore provide an extremely useful complement to research projects also carried out in the BAuA which deal directly with specific aspects of noise and its effects, such as the impact of noise on reading or concentration (see e.g. [12]).

This contribution contains an overview of some of the issues considered during the last years, using the data on noise and disturbing sounds of the BIBB/BAuA Employment Survey. Some example results from the selected topics will be presented here.

The following aspects are addressed in this contribution:

- Basic analysis for the items on “noise” and “disturbing sounds”
- Results regarding activities with varying job requirement levels
- Results with the focus on workers in low-skilled jobs
- Results on disturbing sounds in relation to some items on health aspects

First, in the section “Methods,” the general approach of the survey as well as the items regarding noise and disturbing sounds are described. Since various aspects are then addressed, that are associated with different other items of the survey or different subgroups of participants, these aspects are presented in different subsections in the “Results” section. Furthermore, each of these subsections also includes more information on the particular motivation and, if necessary, further information on the particular methods.

METHODS

The survey in general

The total number of respondents in each of the surveys since 2006 was about 20,000. The participants were at least 15 years old and worked in a paid activity of at least 10 hours per week. In this contribution results from the surveys in 2018 and 2024 are presented. The exact total numbers of participants in these years were 20,012 in 2018 and 20,006 in 2024. In order to ensure that the group examined was as homogeneous as possible in terms of exposure times, the following analyses were restricted to the group of full-time workers, that were 14,767 in 2018 (73,8 % of the total sample) and 14,474 in 2024 (72,3 % of the total sample). Further information on the number of participants included in the calculations for each specific analysis is provided in the respective section or in the corresponding figure captions.

The survey is carried out as a telephone interview (Computer Assisted Telephone Interview (CATI)) which takes on average about 40 minutes and contains more than 300 questions in total. However, not all questions are used for all participants.

Following each survey, the data were weighted in accordance with the outcome of the Microcensus conducted in Germany on an annual basis, in combination with the Labour Force Survey. For example, after the 2024 survey, the data were weighted using the 2023 Microcensus results [13]. For this weighting, some combinations of the sample characteristics (e.g., age, gender, and education) were used in order to describe the current labour force as accurately as possible. The descriptive analyses are all based on weighted datasets.

The questions on “noise” and “disturbing sounds”

The questions on “noise” and “disturbing sounds” are part of a section covering the working conditions. The interviewers introduce this section by stating: “Let’s now turn to various working conditions and whether these occur “frequently”, “sometimes”, “rarely”, or “never” in your role as [job title].”

Among other working conditions the respondents were asked to answer this question for the items “Working under noise” and “Working under disturbing sounds”. In the case that they answer “frequently” they are also asked “Do you feel burdened by this?”. This question could be answered with “Yes” or “No”. If respondents selected “frequently” in response to the question on disturbing sounds, and if they stated that this is a burden for them, a further question was added: “What is the main cause of the burdening sound?”

To answer this additional question, the participants could choose one out for four given options:

- Machines or equipment in your work environment
- Sounds from outside (e.g. road traffic noise)
- Speech
- Other

The item “Working under noise” has been part of all BIBB/BAuA Employment Surveys so far. The item “Working under disturbing sounds” was first included in the survey in 2018.

Most analyses with respect to the acoustical work environment were carried out for both questions (“noise” and “disturbing sounds”) from both surveys. For this contribution the results just for one of the items or for one year are included in some cases. Further analyses can be found in the publications listed in the references.

RESULTS

Basic analysis for the items on “noise” and “disturbing sounds”

The first step was to calculate the percentage of responses in each of the four response categories (frequently, sometimes, rarely, never) and to determine the percentage of people who felt burdened when they had chosen the category “frequently”. For the item “disturbing sounds” also the percentages for the main causes for the disturbing sounds were calculated. Figure 1 shows the results for both items from both surveys (2018 and 2024). In Table 1 the main causes for disturbing sounds in the survey 2024 are listed. The results of this basic analysis are published in [14; 15] and also in [3].

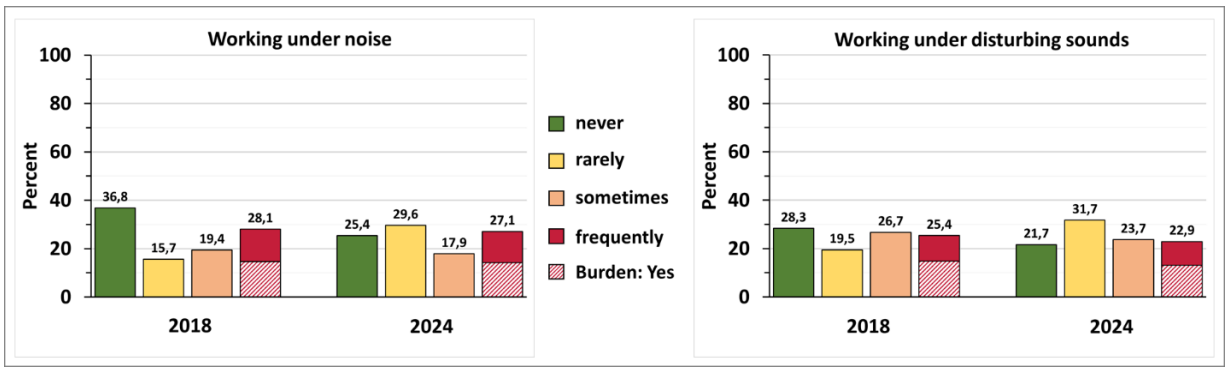

Figure 1: Percentage of full-time workers in each of the four response categories (never, rarely, sometimes, frequently) in both surveys (2018 and 2024) for the question “Working under noise” (left panel) and for the question “Working under disturbing sounds” (right panel). The shaded areas in the columns “frequently” show the proportion of respondents who experienced this as a burden. Source: BIBB/BAuA Employment Surveys 2018 and 2024; for both surveys: *n* > 14,000; weighted results, rounding errors possible.

Table 1: Percentage of main causes of burdening sounds, for full-time workers who had frequently to work under disturbing sounds and experienced this as a burden. Source: BIBB/BAuA Employment Surveys 2024; *n* = 1,890; weighted results, rounding errors possible.

Main cause for the burdening sounds	Percentage
Machines or equipment	53,4 %
Sounds from outside	9,9 %
Speech	28,8 %
Other	8,0 %

Figure 1 shows that the fraction of workers stating that they have to work frequently under noise or under disturbing sounds was about a quarter for both items and comparatively stable in both surveys. The percentages in the category “frequently” were around 3 and 4 points higher, respectively, for the question on noise than for the question on disturbing sounds. A striking result is that the percentage in the category “never” in 2024 was clearly smaller than in 2018, and that the percentage in the category “rarely” has increased. This is even more obvious for the item “noise” than for the item “disturbing sounds”. However, the percentage for the response categories “never” and “rarely” combined has remained roughly the same. The percentage of respondents stating that they experienced the frequent work under an adverse acoustical condition as a burden was higher for the question on “disturbing sounds” (2018: 58,1 %; 2024: 57,0 %) than for the question on “noise” (2018: 52,3 %; 2024: 52,3 %). Regarding the results on the burdening sounds, the highest percentage was found for

“machines or equipment in the work environment”, followed by “speech” and “sounds from outside” (see Table 1 for survey 2024).

Job requirement level

The main question for the following analyses was, whether the distribution of percentages in the four response categories is similar or different, depending on the respective job requirement level. The surveys included questions about the current occupation: “What occupational activity are you currently engaged in?” The responses to this question were the main basis for a classification according to the German “Klassifikation der Berufe 2010” (KldB2010) [16] *(translated: “German Classification of Occupations 2010”).* Part of this classification is the assignment of the occupation to a particular “job requirement level”. The job requirement level in the KldB2010 is defined as a vertical dimension that reflects the degree of complexity of an occupation, and it is graded along the vocational qualification that is usually required to work in this job.

In total four different steps of the job requirement level are defined:

- 1: Unskilled or semi-skilled activities
- 2: Specialist activities
- 3: Complex specialist activities
- 4: Highly complex activities

Looking at the different job requirement levels is of special interest because there are some similarities to the categories of activities defined in the Technical Rules for Workplaces “Noise” (ASR A3.7) [17], which are in force in Germany. In these Technical Rules different rating levels that must not be exceeded during certain activities are listed. The rating level (L_r) is composed of the A-weighted equivalent continuous sound pressure level (L_{pAeq}) during a particular activity plus a penalty of max. 6 dB in case of impulsiveness and/or tonality and/or informational contents ([17], section 3, definitions, 3.3). The maximum allowed rating level varies with the extent to which concentration and speech intelligibility are required for the particular activity. The categories in both systems (job requirement level; categories of activity) are not identical and they are derived from different backgrounds, but as they exhibit certain similarities an analysis considering the job requirement levels appears to be valuable (see [15] and [18]).

In Figure 2 the results for the item “Working under noise” in different groups of job requirement levels are visualized for the surveys in 2018 and 2024. The proportions of participants stating that they feel burdened by frequently working under noise are listed in Table 2.

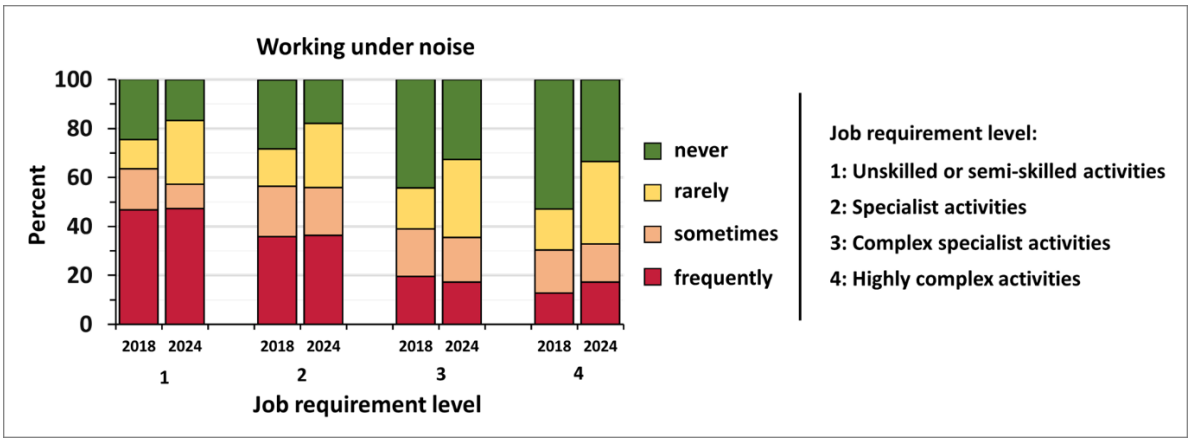

Figure 2: Percentage of full-time workers in each of the four response categories (never, rarely, sometimes, frequently; “stacked”) for all job requirement levels, for the question “Working under noise” in both surveys (2018 and 2024). Source: BIBB/BAuA Employment Surveys 2018 and 2024; in both surveys: n > 14,000; weighted results, rounding errors possible.

Table 2: Percentage of full-time workers who stated to work frequently under noise and experienced this as a burden, listed for each job requirement level in 2018 and 2024, respectively. Source: BIBB/BAuA Employment Surveys 2018 and 2024; people who selected “frequently”: 2018: *n* = 4,139; 2024: *n* = 3,864); weighted results, rounding errors possible.

Job requirement level	**Percentage “burdened” when frequently affected**	
	2018	**2024**
Unskilled or semi-skilled activities	55,6 %	59,2 %
Specialist activities	49,4 %	49,8 %
Complex specialist activities	52,9 %	49,5 %
Highly complex activities	67,2 %	62,2 %

Figure 2 and Table 2 indicate: There was a decrease in the proportion “frequently working under noise” with increasing job requirement level (from level 1 to level 4: 2018: 46,7 %, 35,9 %, 19,6 %, 12,7 %; 2024: 47,3 %, 36,3 %, 17,3 %, 17,2 %). The highest percentage for the response “Yes, burdened by this” were found for the highest job requirement level (2018: 67,2 %; 2024: 62,2 %), but also for the other job requirement levels, the respective proportion of workers stating that they feel burdened by frequently working under noise were around 50 percent and more. This observation is the basis for the analysis that will be presented in the next section.

Workers in low-skilled jobs

The results with respect to the different job requirement levels had demonstrated that even in the group with the lowest job requirement level, nearly 60 percent of the workers stated that they feel burdened by frequent work under noise. The activities carried out by workers in this group are probably not typical for the activities for which the rules define a particularly low rating level. However, this group was comparatively small, with *n* = 447 in the survey 2024. Therefore, a different categorisation was employed for further analyses, a categorization that allows to look at the group of “workers in low-skilled jobs”.

In this contribution results from the survey 2024 are presented. For this analysis also participants in “self-employed work” were excluded from the sample, in addition to the part-time workers. The remaining sample had 13,079 participants. The group of “workers in low-skilled jobs” in this sample comprised 1,519 persons. In principle, the group of workers in low-skilled jobs can be defined in different ways [19]. In the BIBB/BAuA Employment Survey an activity-based definition is used. According to this definition, low-skilled jobs are those for which the particular activities do not require any specific training (see e.g. [20]). The other two groups considered here are “workers in medium-skilled jobs” and “workers in high-skilled jobs”.

Table 3 lists the percentage of employees, stating to work frequently under noise or disturbing sounds in the three groups of employment in the survey 2024. Figure 3 shows the results separately for two different employment sectors, namely the “services sector” and the combined “industrial and agricultural sector”.

Table 3: Percentage of participants frequently working under noise or disturbing sounds in each auf die three groups of employment and the proportion of workers burdened by this. Source: BIBB/BAuA Employment Survey 2024; people who selected “frequently”: noise: *n* = 3,647; disturbing sounds: *n* = 3,121; weighted results, rounding errors possible.

	Noise		**Disturbing sounds**	
Employment groups	percentage “frequently”	proportion of those “burdened”	percentage “frequently”	proportion of those “burdened”
Workers in low-skilled jobs	38,8 %	46,3 %	30,7 %	49,4 %
Workers in medium-skilled jobs	34,2 %	51,3 %	29,0 %	55,7 %
Workers in high-skilled jobs	17,3 %	63,5 %	15,9 %	67,6 %

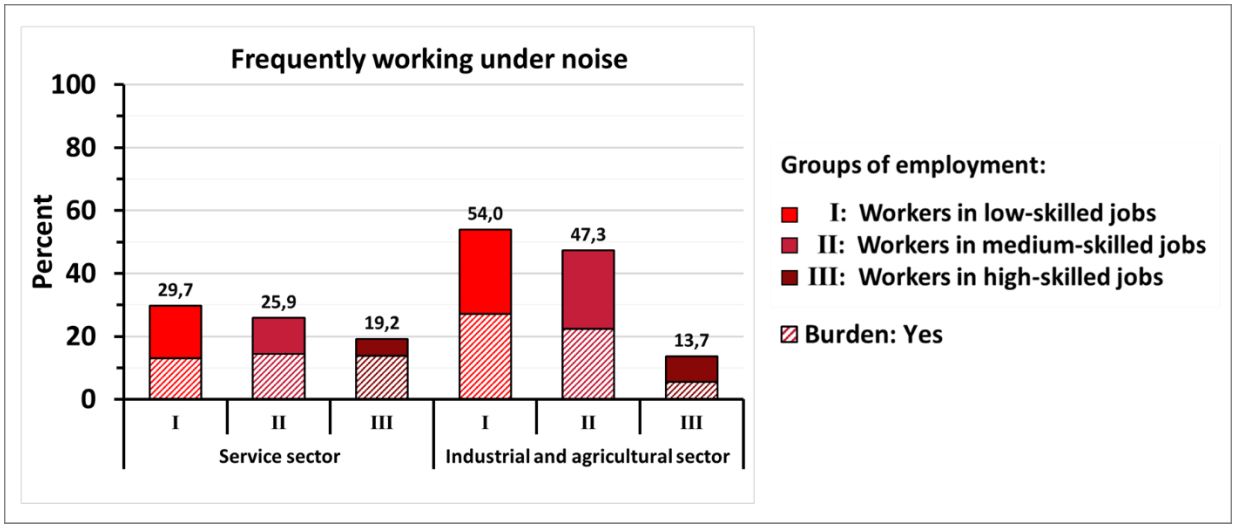

Figure 3: Percentage of participants frequently working under noise in each auf die three groups of employment, separately for the “service sector” and the “industrial and agricultural sector”. The shaded areas show the proportion of respondents who experienced this as a burden. Source: BIBB/BAuA Employment Survey 2024; total number of participants in sectors I to III who selected “frequently”: *n* = 3,546; weighted results, rounding errors possible.

Table 3 shows that the highest proportion of employees stating that they have to work frequently under noise or under disturbing sounds is found in the group of “workers in low-skilled jobs”, closely followed by the group of “workers with medium-skilled jobs”, and with a certain span the group of “workers with high-skilled jobs”. Similar to the analysis regarding the job requirement level, the proportion of employees stating that they feel burdened by frequently working under noise was highest in the group with high-skilled jobs. But again, also in the other groups of employment the proportion of burdened employees was close to 50 percent.

Figure 3 illustrates that the highest proportion of employees frequently affected by noise is found in the industrial and agricultural sector, again with the highest proportion in the group of “workers in low-skilled jobs” and the lowest proportion in the group of “workers with high-skilled jobs”. More results on this topic were presented during “52. Jahrestagung für Akustik” (52nd Annual Conference on Acoustics of the German Acoustical Society (DEGA) [21] in March 2026 and are to be published as a BAuA Fact sheet at the end of 2026.

Results for specific occupational sectors

Because of the large number of questions and participants in the extensive dataset of the BIBB/BAuA Employment Survey, it is also possible to look at specific occupational fields, as long as the sample size in a particular field is large enough to carry out certain analyses. This has been done for example for a presentation during a symposium of the German Acoustical Society held in 2023 on the topic "Akustik und Lärm in Büro und Schule" *(translated: Acoustics and noise in offices and schools";* for more information about the entire symposium, see [22]). For this symposium, an analysis with a special focus on office-based jobs and teaching professions was carried out. Figure 4 illustrates one of the findings, where the results for the two mentioned occupational fields were compared with the results for the field of "metal production, metal machining and metalworking occupations", regarding the main causes of disturbing sounds. The subsets were taken from all full-time workers in the survey 2018. Again, the question on the main causes was only asked to those participants who had stated that they have to work frequently under disturbing sounds and that they feel burdened by this.

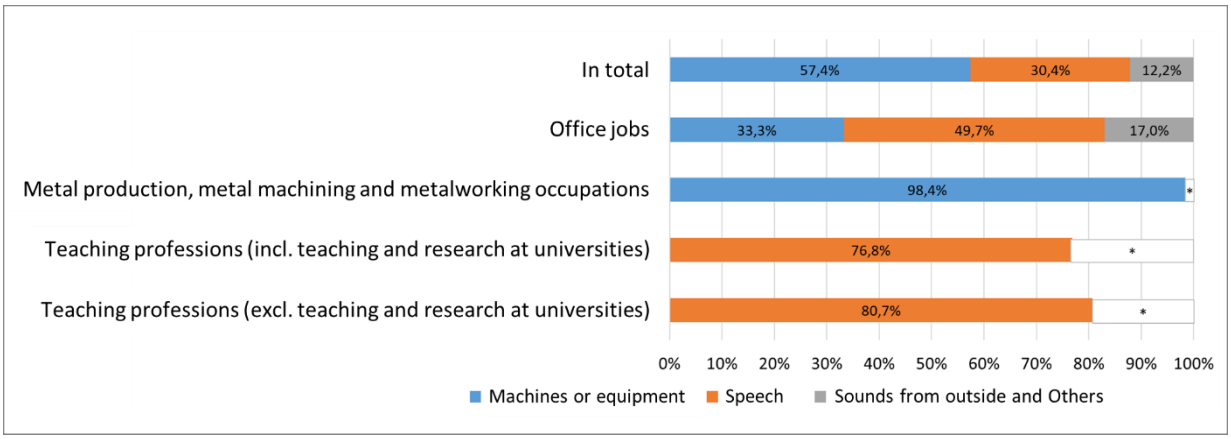

Figure 4: Percentage of main causes of burdening sounds, when participating full-time workers stated to work frequently under disturbing sounds and experienced this as a burden, for the entire group (top bar) and separately for different occupational fields. Source: BIBB/BAuA Employment Surveys 2018; total number of participants who selected "frequently" and feel burdened: n = 2,170, *: case numbers n < 50; weighted results, rounding errors possible.

Figure 4 illustrates that there were large differences regarding the main cause for disturbing and burdening sounds. Whilst in the "metal professions", the sounds from machines or equipment clearly dominate the results, speech was the main source in teaching professions. For office jobs a mixture was found, but speech had the highest proportion in this group with nearly 50 percent.

Considering health aspects

A common question regarding noise or disturbing sounds at the workplace is the question, whether the adverse acoustical work environment has detrimental effects on health and well-being. The following analyses cannot really answer this question, because only descriptive results are reported. Still, the observations for these aspects may serve as a motivation or a starting point for specific studies on this particular topic. Figure 5 shows one result based on data from the survey 2018 considering the responses to some selected health-related aspects, which are part of the "health section" in the BIBB/BAuA Employment Survey, in relation to the question on disturbing sounds. Asking for health aspects is done by the question: "… and have you frequently experienced the following symptoms at work or on working days over the last 12 months?"

This result is part of a BAuA Fact sheet dealing with the question, whether disturbing sounds at the workplace are a burden for employees [7]. For this analysis the group of workers frequently affected by disturbing sounds is compared with the group answering that they are sometimes, rarely or never affected by disturbing sounds (summarised as “not-frequently”).

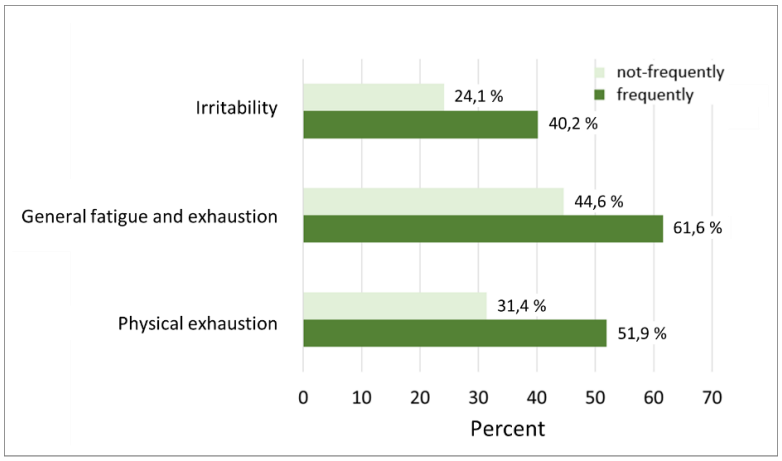

Figure 5: Percentage of yes-responses to questions on specific health-related issues, separately for those, who stated to work frequently under disturbing sounds and those, who sometimes, rarely, or never work under disturbing sounds. Source: BIBB/BAuA Employment Survey 2018; initial sample size *n* = 14,754; weighted results, rounding errors possible.

Figure 5 shows that in the group of workers stating that they frequently have to work under disturbing sounds, a higher proportion of participants reported irritability, physical exhaustion and general fatigue than in the other groups.

The two different items “noise” and “disturbing sounds”

As explained above, all participants got two different questions regarding the acoustical work environment - one question on noise and another question on disturbing sounds. In a recent manuscript (submitted), it is considered whether the two different questions lead to different results regarding the respective proportion in the four response categories “frequently”, “sometimes”, “rarely”, “never”. As a brief prospect, most respondents decided for the same category in both questions, but also other combinations of the two responses are found. This includes even participants stating that they have to work frequently under noise but never under disturbing sounds, and vice versa.

SUMMARY AND OUTLOOK

This contribution analyses data with regard to questions concerning noise and disturbing sounds at the workplace from the BIBB/BAuA Employment Survey, a comprehensive survey conducted in Germany. The data from this large-scale survey provide a good basis for gaining insights into the current state of certain aspects that are relevant in the work context – in this case, with a focus on the acoustical work environment. Along some example results, it was demonstrated that findings on a specific topic can also be reflected upon in the context of other questions in this survey or in relation to specific subgroups within the sample. As those frequently affected are asked about their perceived burden, the survey also provides information on the potential effects of unfavourable acoustic working conditions.

The topics examined here were derived from relevant issues relating to the acoustical environment at the workplace, for example, in an attempt to link findings for different job requirement levels with the categorisation of activities set out in the “Technical Rules for

Workplaces – Noise" (ASR A3.7) [17] to assist employers in fulfilling the requirements of statutory OSH regulations in Germany. The findings obtained in this context showed that the proportion of employees who frequently work under noise or disturbing sounds varies clearly with the job requirement level of the respective activity.

The conclusion drawn from these analyses was that the proportion of employees who felt burdened when having to work frequently under noise or disturbing sounds was highest among those groups of workers in jobs with a high job requirement level or high-skilled jobs. However, it was also found that in the other categories of job requirement levels or employment groups, the proportion of those who felt burdened by frequently working in unfavourable acoustic conditions was around 50 percent. These findings may contribute to the discussion on rating levels or daily noise exposure levels that must not be exceeded in particular work places or during certain activities.

The findings on health-related aspects provide a useful basis for taking these into account in studies that specifically examine the effects of noise on workers. However, when health-related aspects are investigated in connection with the potential effects of the acoustical working environment, it is essential to bear in mind that other factors associated with the work in question may also contribute to these findings and should therefore be considered or controlled for. This holds for all analyses where causal effects are under investigation.

As mentioned above, a further manuscript to be submitted for publication in a journal deals - amongst other things - with the question, to what extent the two different items "noise" and "disturbing sounds" led to different results. This methodological aspect will be investigated in more detail in the future, in order to find out which questions or which descriptions fit best with specific occupational fields. This aspect is important to avoid misunderstandings about existing problems in connection to noise or disturbing sounds at the workplace, as well as about necessary and appropriate measures to take care of this issue.

To date, all considered results were restricted to the group of full-time workers or, respectively, full-time workers in dependent employment, in order to analyse a largely homogeneous group of exposure. For future calculations the group of part-time workers should also be considered, especially in occupations or occupational areas where there are many part-time workers.

The analyses carried out so far for different occupational fields suggest that this approach should be pursued, provided that the groups remain large enough to carry out the required calculations. For example, these analyses appear to be useful for learning more about the main causes of disturbing and burdening sounds in various occupational fields or even in individual occupations. These results can also provide useful information regarding which specific occupational safety measures appear appropriate for particular occupational groups performing specific activities.

In addition to the BAuA research projects that address explicitly noise and its effects, working with selected data from the BIBB/BAuA Employment Survey is being continued in order to gain a more comprehensive picture of workplace noise exposure. Furthermore, the findings will continue to be published in various formats, in order to increase their visibility and to reach different target groups.

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Effects of noise on sleep: a summary of the current state of research from 2023 to 2026

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ABSTRACT

This review summarizes recent research on the impact of environmental noise on sleep. A PubMed search applying the search terms "noise" and "sleep" for titles and abstracts identified 611 publications between April 2023 and February 2026. A stepwise selection process including only original research on humans and publications in English, followed by title and abstract screening, resulted in 118 eligible studies.

The included studies addressed a broad spectrum of noise sources, including neighbourhood, (daytime) occupational, wind turbine, transportation, white, and hospital noise. Hospital-related research clearly predominated, with 48 studies focusing on sleep in hospitalized patients. Many of these investigated the effect of interventions to reduce ward or intensive care unit noise levels, alongside complementary approaches such as earmuffs, music therapy or white noise application.

Sleep outcomes were predominantly assessed using self-reports and less often using wrist actigraphy. The application of other comprehensive physiological assessments, such as polysomnography, was rare. Research maintained a strong focus on vulnerable populations, including neonates, infants and (pre-)adolescents, older adults, individuals with medical conditions, and those exposed to irregular work–sleep schedules.

Co-exposure to additional environmental stressors in the bedroom such as artificial light, particulate matter, humidity, and temperature has partly been considered. Several studies further examined the direct and indirect associations between nocturnal noise exposure, impaired sleep, and adverse mental and cardiovascular outcomes. However, the mediating role of sleep disturbance in the pathway between environmental noise and health effects as proposed by the WHO Environmental Noise Guideline was not consistently supported across studies.

INTRODUCTION

Restorative, undisturbed sleep is fundamental to physical and mental well-being. Chronic sleep restriction and fragmentation have been consistently linked to impairments in mood regulation, cognitive performance, and the homeostatic control of endocrine, metabolic, and cardiovascular systems, thereby increasing the risk of cardiovascular disease, type 2 diabetes, obesity, and mental health disorders such as anxiety and depression [1].

Nocturnal environmental noise is a major contributor to sleep disturbance, particularly in urban environments. A growing body of evidence demonstrates that exposure to nighttime noise – whether from traffic, aircraft, or other sources – induces acute sleep disturbances and degrades overall sleep quality, as confirmed by both objective physiological measures (e.g., polysomnography, actigraphy) and subjective self-reports.

According to the latest assessment by the European Environment Agency [2], noise pollution ranks as the third leading environmental health risk in Europe, following air pollution and inadequate temperature. It is estimated that 72.05 million Europeans (16% of the EU population) are exposed to nighttime noise levels (L_{night}) ≥50 dB – the reporting threshold established by the European Environmental Noise Directive (END) [3]. When applying the more protective thresholds recommended by the World Health Organization (WHO) [4], which are up to 10 dB lower than the END thresholds, the proportion of the population exposed to potentially harmful noise levels rises to approximately 30%.

The adverse health effects of noise exposure are mediated through interconnected biological pathways, primarily via chronic stress activation and sleep disruption. These mechanisms can subsequently trigger systemic inflammation and oxidative stress [2, 5], positioning sleep disturbance as potential key biological mediator in the causal pathway from noise exposure to chronic disease [4].

This review synthesizes original research published over the past three years on the impact of environmental noise on sleep. It extends beyond transportation noise to encompass a broader range of sources, including neighborhood and mixed noise, wind turbine noise, hospital noise, and occupational noise. The review also briefly summarizes recent evidence on noise-reduction interventions. Rather than focusing exclusively on the detrimental effects of noise, the review also evaluates the therapeutic potential of sound-based interventions, including white and pink noise. Special attention is given to individual vulnerability factors, such as age, shift work, and co-exposure to other environmental stressors (e.g., air pollution, light at night). The review concludes with an overview of emerging insights into the mediating role of sleep disturbance in the causal pathway linking noise exposure to adverse health outcomes.

METHODS

A PubMed search using the terms *"noise"* and *"sleep"* in titles and abstracts identified 611 publications between 1 April 2023 and 1 February 2026. The search string employed was: *(("Noise"[Mesh] OR noise[Title/Abstract]) AND ("Sleep"[Mesh] OR sleep[Title/Abstract])) AND ("2023/04/01"[Date - Publication] : "3000"[Date - Publication]).*

To manage the large volume of results, a stepwise selection process was applied. Only original research studies focusing on human participants and published in English were retained using PubMed's filtering system, reducing the initial pool to 330 records. These were then screened based on title and abstract for relevance. Of the 330 papers, 213 were excluded for the following reasons – multiple exclusion criteria could apply to a single study:

- 38 papers were out of scope, focusing on outcomes other than sleep
- 5 papers examined only sleep as a risk factor for other health outcomes
- 10 papers were prospective studies or protocol-only reports

- 82 papers addressed noise or sleep in isolation, without examining their association
- 10 papers did not quantify noise exposure (i.e., lacked systematic variation or observation of noise levels)
- 4 papers were opinion pieces or commentaries
- 63 papers focused on novel sleep measurement methods or related technical developments
- 1 paper involved animal models
- 1 paper was a narrative review

This process yielded 116 eligible papers. In addition, two further studies identified by the author were included based on expert knowledge, bringing the total number of papers reviewed to 118.

The subsequent review is structured according to the following thematic aspects, with individual papers potentially contributing to multiple categories:

- *Noise sources*: Road, rail, and aircraft noise (including military aircraft), neighbourhood noise and mixed or multiple noise sources, occupational or workplace noise, wind turbine noise, white and pink noise, and noise in healthcare settings (e.g., hospital wards and intensive care units).
- *Target populations*: General working-age adults, children (including neonates, infants, school-aged children, and pre-adolescents), adolescents, and older adults.
- *Exposure context*: Single noise exposure versus co-exposure with other environmental stressors, including light at night, air pollution, humidity, and temperature.
- *Health outcome focus*: Sleep as the primary outcome variable versus sleep as a potential mediator in the pathway linking noise exposure to broader health outcomes and chronic diseases.
- *Sleep assessment methods*: Objective measures (e.g., polysomnography, actigraphy, and other simplified physiological indicators) and subjective assessments (e.g., self-reported sleep quality, sleep duration, and sleep disturbance via questionnaires or surveys).
- *Study design*: Observational and experimental studies, including those that evaluate or implement noise-reduction interventions (e.g., sound insulation, noise-masking strategies, operational changes).

RESULTS

Due to the substantial body of research on noise in hospital and care environments, this review provides an extended discussion of hospital noise. Non-hospital noise studies are then summarized, with distinctions made according to the noise source. Moreover, separate sections are dedicated to noise/sound-related interventions, vulnerability factors, environmental co-exposures, a consideration of sleep as outcome versus mediator variable, and a comparison between objective and subjective sleep measures.

Hospital noise

48 of the selected papers [6-53] investigated sleep quality in a hospital context including general wards, specified medical departments (e.g., oncological or orthopaedic wards), intensive care units (ICU) and intermediate care units, postoperative units, outpatient clinics as well as neonatal and paediatric units. The majority were retrospective before-after or cohort studies conducted in China, with a smaller number from Europe, Australia, the Middle East,

and North America. In this review, hospital noise subsumes all noise sources occurring in a medical care setting including noise from medical equipment, alarms, staff conversations, other patients, footsteps and other noises produced by hospitalization.

Hospital noise was significantly associated with impaired sleep quality in patients spanning the entire age spectrum, from premature neonates to elderly adults. Noise was cited as the most common sleep disruptor in an ICU study where 96.4% of patients identified it as a cause of sleep disruption [25].

The primary noise sources identified were medical equipment alarms [6, 25, 49], staff conversations [25, 47, 52], and patient-related noise, such as call bells, groans, other patients [6, 8, 50, 52], cleaning and care activities [26, 44], heating, ventilation, and air conditioning systems and doors [30, 35], as well as footsteps and equipment movement [11, 18, 22, 53].

The overwhelming majority of studies (42 of 48) relied exclusively on subjective self-report questionnaires – most commonly the Pittsburgh Sleep Quality Index, PSQI (22 studies), and Richards-Campbell Sleep Questionnaire, RCSQ (8 studies), while only three studies employed polysomnography [9, 11, 30] and three used actigraphy [13, 16, 26].

Noise exposure was objectively quantified via sound level meters in most studies, though a minority did not measure noise levels directly [34, 38, 39]. Most studies used calibrated sound level meters or precision-pulse meters to quantify environmental noise [10-12, 27, 28, 32, 37]. Some employed continuous 24-hour monitoring systems [18, 26, 29, 37], while others recorded at specific time intervals [17, 21, 22, 44]. One study used a smartphone application [8], and another used noise badge dosimeters worn by patients [6]. Real-time noise monitoring was used in one burn unit study [18]. A minority of studies did not objectively quantify noise [7, 25, 33, 34, 38, 39, 45] but relied on subjecitve reports.

Five studies enrolled neonates (gestational age 24-37 weeks) [9, 13, 16, 31] or infants and preschoolers (5 months to 5 years) [26]. One study enrolled children aged 6-14 years with asthma [21]. One study included patients from neonates to those over 18 years, though age-specific subgroup analyses were not conducted [10]. Several studies enrolled adults with mean ages in the 30s to 50s [15, 20, 40, 46, 47, 50, 53]. Several studies focused specifically on elderly populations, including patients aged ≥65 years with orthopaedic fractures [28], ≥60 years with gastrointestinal stromal tumours [22], ≥60 years with chronic renal failure [51], and patients aged 50–85 years with vertebral fractures [12]. The majority of studies enrolled adult populations spanning wide age ranges (18-75 years or similar) without conducting age-stratified analyses [6, 7, 27, 36].

The 13 purely observational studies characterized the hospital noise environment and correlated noise exposure with sleep outcomes without implementing any noise-reduction measures. 35 intervention studies were identified, with 34 studies applying measures to reduce noise or to attenuate personal noise levels whilst one study investigated an audiobook intervention to mitigate environmental stressors rather than directly reducing noise [25]. Intervention measures comprised the following measures and interventions:

- Architectural changes & facility modifications (e.g., quiet zones, environmental acoustic optimization, sound insulation)
- Equipment modifications (e.g., soundproofing materials, low noise-equipment, equipment maintenance & renovation, alarm volume adjustments)
- Staff behavioural interventions (quiet time protocols, communication training, nursing/care restructuring, door closing policies)
- (Nighttime) noise management & dynamic noise monitoring
- Patient education components
- Personal hearing protection (e.g., earplugs, earmuffs)
- Music therapy

- Audiobook listening
- White noise exposure
- Combined measures/multifaceted noise control

Among the intervention studies, only four were randomized controlled trials [13, 16, 40, 45]. 34 reported significant sleep improvements, with the sole exception being a study that reduced alarms by 81% but failed to lower overall ambient sound levels [35]. Sleep quality improvement was shown, e.g. by increase self-reported sleep quality (e.g., lower PSQI-scores [e.g., 37, 47, 48, 52], higher RCSQ score [e.g., 29] fewer awakenings [16] and less wake time with increase in total sleep time and sleep efficiency [11, 13, 16]. Multifaceted interventions combining architectural modifications, behavioural protocols, and personal hearing protection (such as earmuffs) achieved the largest noise reductions (12–20 dB) and most robust sleep benefits [12, 18, 27, 29] compared to those relying solely on staff education or alarm management [35].

Beyond sleep quality itself, noise exposure and noise reduction were associated with several secondary outcomes across age groups – presumably mediated by improved sleep quality. Psychological distress, measured e.g. via depression and anxiety scores were reduced after noise reduction [14, 15, 19, 36-39, 52]. Physiological stress markers, such as salivary cortisol [12, 28, 37], norepinephrine [23], heart rate variability [37], and blood pressure [29, 42, 43] were related to the noise levels. Pain scores were related to noise levels in several populations [12, 17, 28]. Moreover, noise reduction was associated with shorter hospital stays [27-29, 37, 43].

Non-hospital noise

The 70 included sources [54-123] encompass a broad range of study designs, populations in the whole life span from infants to older people, multiple noise sources, and geographic contexts all over the world, but with a focus on Europe, Asia and Northern America. Study designs were predominantly observational and cross-sectional, with fewer prospective longitudinal studies [62, 69, 102, 107] and a small number of interventional designs including before-after observational studies of natural experiments (night-flight bans, pandemic-related flight reductions, [75, 101], randomized or quasi-randomized trials [79, 122], and pre-post interventions [57, 80, 98]. Noise sources span environmental transportation noise (road, aircraft, rail, wind turbine, military aviation), occupational and workplace noise, neighbourhood noise, and therapeutic sound (white, pink, brown noise). Two studies included in this section fall under the category of occupational noise, despite focusing on hospital noise, as the examined populations consisted of healthcare workers rather than patients [80, 106]. Populations range from infants [89] to children and adolescents [73, 87, 104, 109], adults across the working-age lifespan (investigated in the vast majority of the papers), to older adults [71, 97, 111, 119].

Sleep was most commonly assessed by subjective self-report instruments, particularly the Pittsburgh Sleep Quality Index (PSQI) [71, 86, 88, 106, 117, 123], and less often by objective methods such as actigraphy [58, 78, 104, 118-120] or polysomnography [63, 75, 106, 123].

The overwhelming pattern across studies is a dose-dependent worsening of sleep quality with increasing noise exposure, observed across multiple noise sources, populations, and measurement approaches. The magnitude of association varies considerably by noise metric, study design, and population characteristics. The available evidence on dose-response associations between noise exposure and sleep outcomes is summarized in the following section for multiple noise sources.

Road traffic noise

Among environmental noise sources, road traffic noise is the most extensively studied source and shows consistent adverse effects on sleep across age groups. In older adults in Japan, each 1 dB increase in indoor L_{Aeq} was associated with −0.19% sleep efficiency, +0.66 min WASO, and prolonged sleep onset latency (all $p<0.001$) [119]. In community-dwelling older adults in China, noise from traffic, indoor environments, and public places was significantly associated with lower sleep quality shown by higher PSQI scores [71]. In older adults in Brazil, road traffic noise was associated with OR=1.55 for self-reported poor sleep quality, OR=1.51 for difficulty staying asleep, and OR=1.40 for early morning awakening [111]. In Germany, the critical threshold for 3% (self-reported) highly sleep disturbed was 45 dB L_{night} for road traffic noise, consistent with WHO guidelines [4], while road traffic noise annoyance was greater at lower exposures than international standards would predict [59].

In preadolescents (mean age 12 years) from Dutch and Spanish birth cohorts, each 10 dB increase in outdoor road traffic noise (reported as L_{den}) was associated with −3.62 min total sleep time and +6.88 min WASO collected by wrist-actigraphy, while no association was found with maternal-reported sleep disturbances, underscoring the divergence between objective and subjective measures in younger populations [104]. Adolescents in Switzerland exposed to L_{night} ≥55 dB had an OR=2.43 for self-reported sleep disturbances compared to those exposed to ≤44 dB [109]. In a large Korean cross-sectional study of over 185,000 adults, perceived noise pollution was associated with OR=1.33 for self-reported poor sleep collected via PSQI score [86]. Individual-level personal noise that collected urban noise including traffic noise via portable noise sensors in Hong Kong found that each 10 dB(A) increment in 24 h average sound pressure level increased odds of poor sleep quality by 29% and shorter sleep duration by 24% in adults [91].

An ecological study in the Paris Metropolitan Area, which covered approximately 10.5 million residents, found that each 5 dB(A) increase in L_{night} noise was associated with an additional +1.0‰ hypnotic drug dispensing, with effects significantly greater in those aged >50, women, and socioeconomically deprived residents [65]. A structural equation modelling (SEM) study in Swiss adults found road traffic noise to have negligible direct effects on sleep efficiency as measured by actigraphy, but a direct association with cardiovascular risk, while railway noise was the source most strongly linked to reduced sleep efficiency ($\beta=-0.15$) [118].

A study in India found statistically significant associations between nocturnal traffic noise exposure and insomnia symptoms, particularly difficulty falling asleep (OR = 1.53). Females were more affected than males (OR = 1.68). But no significant association was found between noise exposure and sleep medication use. Participants sleeping with open windows experienced stronger noise-sleep disruptions [103].

Aircraft noise

Aircraft noise consistently disrupted sleep. The UK Biobank study of over 105,000 participants near four major airports demonstrated that L_{night} ≥55 dB versus <45 dB was associated with higher actigraphically measured movement, disrupted sleep-wake cycles (lower relative amplitude, higher intra-daily variability), and higher odds of daytime dozing (OR=1.52) [78]. Individuals over 65 years and those with diabetes or dementia showed larger effect sizes [78]. A pre-post comparison at Frankfurt Airport found a 27.5% reduction in PSG-recorded awakenings following implementation of a night-flight ban ($p<0.001$), with exposure-response modelling confirming that awakening probability increases with maximum sound pressure levels, duration of flyover noise events, and elapsed sleep time, and varies by sleep stage, being highest during REM sleep [75].

In a cohort study of 35,226 nurses around 90 U.S. airports (mean age 66 years), exposure to L_{night} ≥45 dB(A) was associated with greater odds of self-reported short sleep duration (OR = 1.23) [62]. Residents in Japanese communities around Okinawa Air Base with high military aircraft noise exposure had OR=1.98 for self-reported sleep disturbance compared to no-exposure communities [95]. Low-exposure communities were similarly affected (OR=2.04), however, the distinction between low and high-exposure communities was not consistent throughout the considered years. Military aircraft noise exposure in Okinawa was also associated with poor mental well-being, with the ecological design limiting ability to disentangle individual-level confounders [95]. A pooled analysis of four randomized crossover studies found that simulated nocturnal aircraft and train noise significantly impaired self-reported sleep quality, restfulness, and morning feeling (all $p<0.0001$), alongside endothelial dysfunction and increased mean arterial pressure, demonstrating linkage between noise-disturbed sleep and acute cardiovascular effects [79]. At Tan Son Nhat Airport in Vietnam, aircraft L_{night} was a significant predictor of insomnia in the post-pandemic period, though the pandemic context complicated direct exposure-response interpretation [100].

Methodological work applying established exposure-response functions to military aircraft noise near Naval Air Station Whidbey Island estimated between 8,315 and 9,770 persons to be highly sleep disturbed by nighttime noise levels exceeding 40 dB L_{night} [83].

Rail noise

Rail noise generally produces smaller effects on sleep than road traffic noise. In Japan, a secondary analysis of 22 socio-acoustic survey datasets found no large differences in self-reported sleep disturbance across road traffic, conventional railway, and Shinkansen noise sources, with road traffic slightly higher; responses to railway noise in Japan were lower than WHO guidelines [4] and South Korean comparisons [99]. In Germany, the threshold for 3% highly sleep disturbed from railway noise was approximately 53 dB L_{night}, considerably higher than the WHO guideline of 44 dB L_{night} and higher than the equivalent road traffic threshold [59]. A Swiss SEM study found railway noise, but not road traffic or aircraft noise, to be significantly associated with lower actigraphic sleep efficiency [118]. A natural experiment in Japan around the Kyushu Shinkansen found that earthquake-induced behavioural changes (increased bedroom window closure) reduced sleep disturbance in northern detached houses despite similar noise levels, while sudden resumption of high-speed services increased disturbance in southern apartments, illustrating the importance of indoor exposure and context [98].

Occupational and workplace noise

Occupational noise is consistently associated with sleep disturbance. In a Korean tire manufacturing factory, night-shift workers exposed to >80 dB(A) had an OR=3.36 for incident insomnia over four years compared to those at lower noise levels [69]. Among Chinese healthcare workers in emergency departments, nighttime noise levels correlated strongly with PSQI total score (r=0.515), sleep latency (r=0.422), and were negatively correlated with sleep duration (r=−0.503) and sleep efficiency (r=−0.293) assessed via polysomnography, with emergency staff experiencing significantly worse objective sleep than general inpatient staff (all $p<0.0001$) [106]. Among Chinese military personnel (mean age 25 years), cumulative noise exposure directly predicted sleep disturbance (β=0.284, $p<0.001$), with sleep disturbance further mediating 79-86% of the indirect effect of noise on cognitive impairment [82].

In contrast, a cross-sectional study of Tanzanian metal industry workers exposed to 97.9 dB(A) and office cleaners at 76.6 dB(A) found no significant differences in insomnia (assessed via Bergen Insomnia Scale) or daytime sleepiness (obtained via Epworth Sleepiness Scale) after adjustment for demographic confounders [56]. This null finding may reflect residual confounding by socioeconomic and lifestyle factors, limitations of self-report instruments in low-income settings, or the fact that workplace daytime noise does not directly disrupt nocturnal sleep in the same way environmental nighttime noise does. A Korean survey of over 1,200 workers found that health problems from occupational noise significantly predicted self-reported insomnia [84], and a Chinese heavy industry cross-sectional study found sleep disorders to be a primary mediator accounting for 12.4% of the effect of high occupational noise on atrial fibrillation risk [94].

Wind turbine noise

Evidence on wind turbine noise suggests limited direct impact on sleep when turbines are sited responsibly. A Canadian community survey found that the overall prevalence of self-reported high sleep disturbance was not significantly related to wind turbine L_{night} ($p=0.53$), but the probability of attributing sleep disturbance to wind turbines specifically increased significantly with noise level, reaching the 3% highly sleep disturbed benchmark at 33.5 dB(A) [96]. Annoyance towards wind turbines was strongly associated with sleep disturbance [96].

Neighbourhood and multiple noise sources

Several studies examined perceived or aggregate neighbourhood noise. In Australia, greater perceived environmental noise in the neighbourhood was associated with adjusted OR=1.06 for both self-reported insufficient sleep and sleep disturbance [74]. In a large-scale Korean survey, an OR=1.33 was found for poor overall PSQI in those perceiving noise pollution [86]. Earthquake survivors in Turkish container settlements had significant correlations between noise sensitivity and self-reported sleep quality ($r=0.125$-0.147, $p<0.01$), with noise-sensitive individuals experiencing more insomnia and poorer sleep [54]. A cross-sectional study in Hong Kong found that each 10 dB increment in 24h average individual-level ambient noise exposure (including traffic but also other neighbourhood noise) increased odds of self-reported poor sleep quality by 29% [91], see above, already reported under section Road noise. Among Australian mining shift workers, (non-specified) noise among other environmental factors was significantly negatively correlated with reporting to have control over their sleep (including when they go to sleep and wake up and how much and how well they sleep) obtained via the Brief Index of Sleep Control [60].

A methodological study that did not report associations between noise exposure and sleep, however, proposed a new measure to compare exposure-response functions for high sleep disturbance between different sources including aircraft, road, rail, and industry noise [61].

Source-specific differences

Road traffic and aircraft noise consistently emerge as more disruptive to sleep than railway noise at equivalent energy levels in the papers considered for this review. In the French ecological study, road noise had the largest per-decibel effect on hypnotic drug dispensing (+1.0‰/5 dB) followed by recreational, aircraft, and railway noise (+0.3‰/5 dB) [65]. This ordering aligns with German exposure-response data where the road sleep disturbance threshold is 45 dB L_{night} while railway noise reaches the same 3% highly sleep disturbed threshold only at 53 dB [59]. Japanese and German railway data both indicate lower

community response to rail than to road noise at equivalent L_{night}, which has been attributed to the more predictable, temporally regular, and relatively lower spectral content of rail events compared to road traffic [59, 99]. Military aircraft noise, which is highly intermittent, intense, and unpredictable, may be particularly disruptive relative to steady-state metrics, as illustrated by a Japanese study finding sleep disturbance ORs near 2.0 even at community-average noise levels of 40–49 dB L_{night} [95].

Noise reduction interventions

In contrast to the extensive body of research on hospital noise, which includes numerous studies evaluating the impact of noise reduction interventions on patient sleep, systematic evaluations of environmental noise mitigation strategies in non-hospital settings remain limited.

One study employing polysomnography assessed sleep outcomes before and after the implementation of a night-flight ban at Frankfurt Airport [75]. Results showed a significant reduction in the number of nightly awakenings and total wake duration among residents, indicating improved objective sleep quality. In contrast, a general reduction in air traffic during the COVID-19 pandemic did not lead to improvements in self-reported insomnia [101]. This lack of effect may be attributed to heightened psychological stress related to the global health crisis, which could have overshadowed the potential benefits of reduced noise exposure [101]. A pre-post study examining noise barriers along three highway-adjacent residential areas found that while noise exposure was significantly reduced, only one of the three sites reported a corresponding decrease in noise annoyance. No significant improvements were observed in sleep quality or other dimensions of quality of life [57]. Another study investigated the effects of a step change in railway noise exposure – comparing an area with increased exposure due to track elevation and the opening of a new station, and a second area with reduced exposure. Contrary to expectations, the increase in noise exposure was not associated with higher self-reported sleep disturbance, and vice versa. The observed lack of expected associations may have been confounded by changes in window-closing behaviour following an earthquake that occurred between the two survey periods [98]. These findings highlight the complexity of noise–health relationships in real-world settings and underscore the importance of considering behavioural, psychological, and contextual factors when evaluating the effectiveness of noise mitigation measures.

In addition to studies investigating noise mitigation strategies at the source or related to outdoor exposure, several recent studies have demonstrated the benefits of individual-level interventions aimed at noise masking or personal noise reduction. These include the use of noise-masking earbuds [80], white noise [90, 117], and personalized music listening [122, 123], which have shown potential in improving sleep quality.

Therapeutic use of sound

Besides interventions to reduce noise, several studies examined the potential beneficial therapeutic effect of sounds Closed-loop acoustic stimulation (CLAS) using 40 dB pink noise targeted to slow-wave up-phases significantly enhanced slow-wave activity and slow-wave sleep duration in Alzheimer's disease patients across 14 nights [114], with an earlier pilot study reporting a near-doubling of SWS time ($p=0.019$) [115]. White noise combined with cognitive behavioural therapy (CBT) significantly enhanced self-reported sleep quality (indicated by reduced PSQI scores) in adults with depression compared to CBT alone ($p<0.05$) [117], and white noise combined with CBT also improved sleep quality, anxiety, depression, and coping in college students with anxiety and depression disorders [90]. A

quasi-randomized controlled trial using Cranial electrotherapy stimulation (CES) integrated with music (pink noise or double beats) found significant improvements in sleep onset latency and quality of life in adults with insomnia, with the 20-29-year age group showing the best response [122]. A laboratory experiment found that white, pink, and brown noise did not differentially modulate pupil-linked arousal in young adults, suggesting that proposed differential arousal mechanisms may be more complex than commonly assumed [76]. Acupuncture monotherapy for noise-induced sleep disorders in healthcare workers achieved comparable PSQI results to pharmacotherapy, while combined acupuncture and music therapy was superior, reducing PSQI scores from 9.47 to 5.82 and improving polysomnographically measured sleep efficiency from 68% to 85% [123]. A forest environment intervention in Chinese adults achieved noise levels of <50 dB alongside multiple other environmental benefits and showed significant PSQI improvements compared to urban conditions [92].

Vulnerability and amplifying factors

Older adults were the most thoroughly studied specific age group for noise-sleep relationships [71, 78, 97, 111, 119, 121]. Older adults (>60 and 65 years) demonstrate the greatest vulnerability, with amplified objectively measured effects documented for aircraft noise [78] and non-specified mixed indoor noise [119] and also stronger associations between nighttime urban mixed noise and hypnotic drug use from age 50 onwards [65]; those with dementia or diabetes show further elevated susceptibility [78].

Evidence was least for infants and young children. Direct evidence for infants is confined to a neuroimaging study showing individual variability in brain functional connectivity responses to white noise stimulation during sleep, without establishing harm [89]. Objective actigraphy detected significant sleep shortening in preadolescents at transportation and mixed noise levels that left maternal-reported disturbances unchanged [104], indicating that noise-related sleep loss in children may be clinically underrecognized. Higher noise levels were positively associated with self-reported sound disturbance and sleep problems (while access to a domestic garden / green space was protective [73)] as well as with shorter sleep duration and more frequent awakenings in preadolescents [120].

Adolescents exposed to road traffic noise at ≥55 dB had more than double the odds of self-reported sleep disturbances (OR = 2.43) compared to road noise L_{night} ≤ 44 dB [109]. Noise was also a significant driver of nighttime awakenings in pupils aged 12–16 years [112]. Neighbourhood noise alone showed no significant direct effect on hypertension incidence in a large adolescent cohort, but healthy sleep duration was protective (RR=0.63), suggesting that noise may affect adolescent health primarily through sleep disruption rather than independently [72].

Across all age groups, objective sleep measures consistently reveal effects at lower exposure thresholds than subjective questionnaires [58, 104, 119].

Therapeutic pink noise can enhance slow-wave sleep in Alzheimer's disease patients [114, 115], and white noise combined with cognitive behavioural therapy improves sleep quality in adults with depression and anxiety [90, 117].

Noise sensitivity and noise annoyance amplified the relationship between noise exposure and sleep disturbance may have increased vulnerability [54, 109], and green space moderates adverse associations [67, 73]. Non-acoustic factors including perceived economic situation, housing conditions, time spent at home, and chronic illness contributed to sleep disturbance [95] and insomnia [100, 101]

Shift workers are considered a vulnerable population due to forced irregular sleep schedules and associated circadian misalignment. Among the selected studies, three specifically examined the impact of noise on sleep in shift-working populations. A study among mining shift workers found that exposure to noisy sleep environments – without differentiation by noise source – was associated with reduced self-reported sleep control (i.e., perceived ability to regulate sleep onset and duration), likely attributable to poor acoustic insulation in shared living accommodations [60]. Another study reported that high occupational noise exposure during working hours is a significant risk factor for insomnia among male night-shift production workers [69]. Over a four-year follow-up, workers in the high-noise group (>80 dB(A)) exhibited a significantly higher incidence of insomnia compared to those in the low-noise group (OR = 3.36). In a retrospective study of automobile manufacturing workers exposed to low-frequency noise in industrial settings – encompassing morning, midday, and night shifts – only a non-significant trend for a difference in self-reported sleep quality was observed between noise-exposed and non-exposed groups ($p = 0.069$). However, shift timing was not further analysed in this study, limiting the ability to disentangle the independent effects of noise and shift work on sleep [66].

Environmental co-exposure

Data on co-exposure to additional environmental stressors, such as light at night, temperature, air pollution, and humidity, have been collected in several studies. In some cases, these factors were included as covariates in statistical models to adjust for potential confounding, without further reporting or analysing their individual effects on sleep or health outcomes [62, 91, 116]. Eight studies [58, 60, 63, 71, 73, 102, 113, 120] reported main effects for non-noise environmental stressors and one investigated protentional interactive effects between environmental stressors [58].

A cross-sectional study in children aged 8-12 years found that higher levels of road traffic noise exposure and air pollution (NO_2) are associated with increased sound disturbance and sleep problems [73]. In children age 7-9 years, sleeping in a darkened bedroom was associated with longer sleep duration measured via actigraphy [120]. Noise exposure was negatively related to sleep duration in Latino children while for the total sample including also Black and Non-Latino White children, there was only a trend for such an association. However, napping was increased in children with higher nocturnal noise exposure and may have mediated the effect between noise exposure and shortened sleep duration [120]. A cross-sectional study in older adults (≥ 65 years) found an association between exposure to light and noise at night and self-reported poor sleep quality [120]. An association among light disturbance, nocturnal noise and poor self-reported sleep has also been shown among medical students [113]. A study in mining workers investigated the association between pillow/blanket comfort, mattress comfort, room temperature, light, and safety besides nocturnal noise exposure and found throughout negative correlations to self-reported sleep control [60].

In a longitudinal study, sleep duration was self-reported at baseline and after an average of five years of follow-up, and categories of sleep trajectories were built. Residents of neighbourhoods with higher light at night and nighttime noise levels were more likely to experience suboptimal sleep trajectories over time [102]. An observational actigraphy study reported significant associations among bedroom particulate matter (PM2.5), temperature, CO_2 and noise levels and sleep efficiency, with higher exposure levels were associated with lower sleep efficiency. No significant associations with sleep efficiency were found for relative humidity and barometric pressure [58]. No significant interactions were found for all possible pairs of environmental exposures suggesting additive but not interactional effects of co-exposures [58]. In contrast, a retrospective analysis of laboratory studies using

polysomnography found that moderate pre-sleep light or nocturnal noise exposure had no significant effects on ultradian sleep cycle duration in healthy participants [63].

Sleep as outcome versus mediator variable

In a substantial subset of studies on environmental and occupational noise, sleep functioned as a mediator variable linking noise to other health outcomes. Sleep disorders accounted for 12.4% of the association between high occupational noise and atrial fibrillation risk [94]. Sleep disturbance fully or partially mediated the association between bedroom traffic noise and obesity (BMI and waist circumference) among women, but not men, in a Northern European cohort [116]. In military personnel, sleep disturbance explained 79-86% of the indirect effect of noise on cognitive performance, with tinnitus forming a chain mediation pathway that further amplified the sleep-cognition link [82]. In older adults, poor sleep and physical inactivity jointly mediated approximately 15-20% of the association between residential noise and thyroid nodule risk [121]. The fact that sleep mediates noise-cardiovascular and noise-metabolic associations was not supported in one major prospective study in nurses: inadequate sleep duration did not mediate the noise-CVD association, suggesting that either the mediating sleep pathway operates at a finer temporal grain than annual average self-reported duration captures, or that noise-CVD associations are partly mediated by direct autonomic and vascular effects during the noise event itself rather than through cumulative sleep deprivation [107]. A study conducted in Switzerland showed that different noise sources appear to affect different biological pathways: road traffic noise was primarily associated with cardiovascular risk independently of sleep efficiency, while railway noise was primarily associated with reduced sleep efficiency and metabolic risk [118]. This source specificity may reflect differences in spectral composition, temporal patterns, and individual sensitisation.

Objective versus subjective sleep measures

A recurring methodological theme across studies is the divergence between objective and subjective sleep measures in response to noise. In a cohort study with 1076 participants (≥ 60 years) in the Kansai area in Japan, objective actigraphy showed stronger associations with mixed indoor noise than subjective PSQI components [119]. In preadolescents, actigraphy detected significant reductions in total sleep time and increased WASO per 10 dB noise increment, but maternal-reported sleep disturbances showed no association [104]. In the UK Biobank aircraft noise study, actigraphic measures of sleep-wake cycle disruption were significant while self-reported sleeplessness was uncertain (OR=1.13) [78]. Bedroom environmental monitoring (including noise, temperature, humidity, particulate matter, and CO_2) in 62 adults showed that noise reduced actigraphically measured sleep efficiency by 4.7% between the highest and lowest exposure quintiles ($p<0.0001$ while self-reported disturbance by noise was associated with lower efficiency but not significantly [58]. These divergences are not simply measurement error and have been reported before [e.g., 124]. Subjective sleep quality integrates cognitive appraisal, habituation, and psychological factors such as noise sensitivity and annoyance, while objective measures reflect physiological sleep continuity and architecture [124]. Daytime noise from occupational sources may sensitize the nervous system but not directly fragment nocturnal sleep, explaining some null findings in occupational contexts [56].

SUMMARY AND OUTLOOK

Comprehensive research examining the effects of noise on sleep across diverse age groups, noise sources, and methodological approaches highlights the detrimental impact of nocturnal noise on human sleep quality. Nevertheless, several key aspects remain incompletely understood, offering valuable avenues for future research. The review reveals that noise-induced poor sleep can contribute to increased risks for adverse cardiovascular, metabolic, endocrinological outcomes and deteriorated cognitive performance both due to environmental / transportation noise [82, 94, 116, 121] and hospital noise [12, 23, 28, 37]. However, the hypothesized mediating link of sleep disturbance between noise and health outcomes was not found throughout all noise sources and age groups warranting further research of the impact of relevant acoustical patterns (timing, intermittency, spectral composition) as well as a wide range of individual and environmental vulnerability and resilience factors. While noise sensitivity consistently amplifies sleep disruption [54, 109], knowledge on the genetic, psychological, and physiological factors that determine individual vulnerability remains limited. Future studies should investigate environmental resilience factors, including green space availability, as potential buffers against noise-related health impacts [67, 73]. Generally, evidence for the biological pathway as recently proposed [2, 5] according to which sleep disturbances (besides annoyance) induced by noise exposures cause oxidative stress and inflammation that cause the main detrimental health outcomes via alternations in metabolic processes, in the microbiome, endothelial dysfunction, cerebrovascular dysfunction, circadian dysregulation and an Alzheimer's disease like brain is still limited in humans and warrants further investigations.

With regard to data collection methodology, cross-sectional studies relying on self-reported questionnaires remain predominant. While these studies provide valuable evidence linking noise exposure to poor sleep, they are inherently limited in establishing causal direction or elucidating underlying biological pathways. To advance understanding, future research should prioritize longitudinal designs that integrate repeated assessments of both objective (e.g., actigraphy, polysomnography) and subjective sleep measures, alongside relevant biomarkers of stress, inflammation, and circadian regulation.

While a substantial body of research on noise impacts in the hospital setting have demonstrated the benefits of noise reduction measures on sleep quality in patients [e.g., 13, 16, 40, 45], evidence for similar benefits due to reduction of environmental – above all transportation noise – is limited [75]. Future research is encouraged to focus on the systematic evaluation of intervention measures incorporating both self-reports and (simplified) objective sleep measures to detect also small changes in sleep quality.

Although noise effects have been studied across the entire life span, research focusing specifically on young children, adolescents, and older adults remains limited – though it is gradually increasing. The findings reported in this review underscore the need for future research targeting these age groups, particularly due to their heightened vulnerability compared to the general population. For children, future studies should prioritize objective sleep assessments, given the well-documented discrepancies between caregiver-reported sleep and objective measures [104]. Moreover, indoor noise measurements are likely to provide a more accurate estimation of the true relationship between environmental noise exposure and sleep outcomes than outdoor modelled noise levels or self-reported exposure, as they better reflect actual in-situ conditions [98, 119].

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Effects of Aircraft Noise on Sleep: FAA National Sleep Study Results

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ABSTRACT

Aircraft noise can disrupt sleep and impair recuperation. The last U.S. investigation on the effects of aircraft noise on sleep dates back more than 20 years. Since then, traffic patterns and noise levels produced by single aircraft have changed substantially. It is therefore important to acquire current data on sleep disturbance relative to varying degrees of aircraft noise exposure in the U.S. FAA's National Sleep Study collected objective and subjective sleep data between September 2021 and October 2023. Seventy-seven U.S. airports with relevant nighttime air traffic from 39 states were included in the sampling frame. The field study aimed to recruit 400 participants from four noise strata and record electrocardiogram (ECG), body movement and sound pressure levels in the bedroom for five consecutive nights. The primary outcome of the study is an exposure-response function between instantaneous maximum A-weighted sound pressure levels of individual aircraft measured in the bedroom and awakening probability inferred from changes in heart rate and body movement. Self-reported sleep disturbance due to aircraft noise is the secondary outcome that will be associated with long-term average noise exposure metrics such as Day-Night Average Sound Level (DNL) and Nighttime Equivalent Sound Level (Lnight). Data collection yielded 38,849 verified aircraft noise events across 1,923 study nights from 402 participants near 56 airports, plus 4,983 survey responses from residents near 76 airports. Key results of the ongoing data analysis will be presented at the ICBEN conference.

At the time of this writing, the final report of the National Sleep Study has not been published. The methodology of the National Sleep Study is described in detail in this open access article:

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Efficacy of Pink Noise and Earplugs for Mitigating the Effects of Intermittent Environmental Noise Exposure on Sleep

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ABSTRACT

Exposure to environmental noise (EN) during sleep is associated with sleep disturbance and adverse health outcomes, yet evidence-based, cost-effective interventions remain limited. This study examined whether pink noise (PN) and earplugs could attenuate the sleep-disrupting effects of intermittent EN. A seven-night polysomnographic laboratory protocol was conducted with 25 healthy adults (mean±SD age 28.5±5.9 years, 7 male) under varying acoustic conditions: EN exposure (93 events; peak levels of 45–65 dBA), continuous PN (40 or 50 dBA), earplugs, and combined interventions. Post-sleep assessments included cognitive testing, cardiovascular and audiometric measures, and subjective questionnaires. Relative to quiet control nights, EN significantly decreased N3 slow-wave sleep ($p<0.0001$), whereas PN reduced REM sleep ($p<0.001$). Awakening probability varied by noise source, decreasing in the order: crying baby, fire alarm, helicopter, low sonic boom, drone, rail, jet, and road noise. Combining PN with EN generally degraded sleep architecture, though modest dose-dependent reductions in arousal frequency and partial N3 restoration were observed. Earplugs effectively counteracted most EN-related sleep impairments, although protective benefits diminished at the loudest EN level (65 dBA). No next-morning noise effects on cognition, cardiovascular parameters, or hearing were detected; however, participants reported poorer subjective sleep quality, alertness, and mood following EN and PN exposure. These findings support earplugs as an effective countermeasure against EN, while PN-associated REM sleep reduction raises concerns about routine broadband noise use - particularly given REM sleep's roles in memory, emotional regulation, and neurodevelopment. Further investigation into optimal broadband noise characteristics and long-term effects is warranted, especially among vulnerable populations.

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How Noise of an Air-Source Heat Pump Affects Sleep in an Experimental Setting

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ABSTRACT

Residential air-source heat pump (AHP) installations are increasing across Europe, yet their impacts on sleep remain insufficiently understood. This study examined whether nocturnal AHP noise affects sleep macrostructure and microstructure, as well as self-reported sleep quality in healthy adults. Forty participants completed a laboratory-based, multi-night polysomnography (PSG) protocol consisting of three counterbalanced conditions: (1) no noise (Baseline), (2) outdoor-recorded AHP noise, filtered as heard through a tilted window ($L_{Aeq,indoor}$ = 30 dB), and (3) outdoor-recorded AHP noise, filtered as heard through a closed window ($L_{Aeq,indoor}$ = 21 dB). From PSG standard macro-sleep parameters, including Total Sleep Time (TST) and Sleep Efficiency (SE), and microstructural changes, specifically noise-associated arousals, were assessed. Self-reported sleep outcomes were evaluated using standardised evening and morning questionnaires.

No significant differences in TST or SE were observed across the three conditions. However, the tilted-window condition elicited a significantly greater number of noise-related arousals compared with the closed-window condition. Participants also self-reported significantly greater sleep disturbance during the tilted-window condition than in both the Baseline and closed-window conditions, with impacts on falling asleep, maintaining sleep, and sleeping in. In the morning after the night with the tilted window condition, sleepiness was greater compared to the sleepiness the evening before.

In conclusion, results indicate that AHP can trigger measurable physiological responses during sleep and significantly impairs subjective sleep quality, particularly at higher noise levels. These findings highlight the need to consider AHP noise exposure when planning and implementing heat pump systems in residential environments.

INTRODUCTION

The ongoing transition from fossil-fuel-based heating towards renewable energy technologies is fundamentally altering the acoustic character of residential neighbourhoods across Europe. Air-source heat pump (AHP) installations are a cornerstone technology of this transition, offering a low-carbon alternative for space heating and hot water provision. Driven by climate policy targets and energy security imperatives, annual AHP installation rates have accelerated sharply in recent years and are projected to continue rising throughout the present decade. Unlike district heating systems or roof-mounted solar thermal collectors, AHPs are typically installed at ground level in close proximity to dwellings, often adjacent to bedroom-facing facades, and are designed to operate continuously, including during night-time hours.

An AHP produce characteristic noise through the interaction of compressor vibration, fan blade rotation, refrigerant flow, and periodic operational mode transitions. The resulting acoustic emission is quasi-continuous in nature, with a pronounced low-frequency spectral component and intermittent amplitude excursions during switching on/off, steady-state operation, ice formation on the outdoor evaporator, active defrost, and cleaning cycles. This temporal and spectral profile differs markedly from the impulsive or event-based character of road traffic, railway, and aircraft noise, and existing noise assessment frameworks developed for these transport sources may not be directly applicable. Community complaints attributable to AHP noise are documented in the literature and in reports from environmental health authorities across several European countries, yet evidence-based indoor noise limit values specifically protective of sleep for this source category remain largely absent from regulatory guidance.

Sleep is a fundamental determinant of health and well-being. Chronic sleep disturbance has been associated with elevated risk of cardiovascular and metabolic disease, impaired immune and cognitive function, and reduced quality of life [1]. The World Health Organization's (WHO) Environmental Noise Guidelines for the European Region classify high sleep disturbance as one of the critical health impacts of environmental noise and recommend source-specific guideline values of 40 dB to 45 dB L_{night} for transportation noise [1]. However, these guidelines do not address stationary residential noise sources such as AHPs, and there is currently no equivalent WHO nighttime guideline for such sources.

In-lab studies using polysomnography (PSG) have characterised the sleep response to transportation noise in considerable detail [2]. Whether AHP noise, with its distinctive acoustic signature, produces comparable sleep responses at indoor levels relevant to realistic window-opening scenarios had not been examined in a controlled multi-night PSG study prior to the present investigation.

This study addressed this gap. Its objectives were: (1) to determine whether nocturnal AHP noise at two indoor levels (approximately 21 dB $L_{Aeq,indoor}$, representative of a closed window, and approximately 30 dB $L_{Aeq,indoor}$, representative of a tilted window) produces statistically significant changes in the macro- or microstructure of sleep as measured by full-night PSG; (2) to assess the effects of each condition on self-reported sleep disturbance across three functional domains; and (3) to characterise the impact of noise condition on morning sleepiness as an indicator of nocturnal recuperation.

The 'sleep study' described in this paper is part of a study combining multi-night PSG and daytime testing to assess the effects of AHP noise on sleep and daytime annoyance, concentration, and mood. Findings on the impact of AHP noise at daytime is presented in [3]. The full combined study is described in detail in [4]-[5].

METHODS

Study Design and Acoustic Stimuli

A randomised, within-subject, double-blind crossover design was employed. Each participant was exposed to three experimental conditions on separate PSG nights, counterbalanced across participants according to a balanced Latin square scheme: (1) a quiet baseline night with no AHP noise playback; (2) a closed-window condition (AHP noise filtered to simulate transmission through a well-insulated, fully closed window, yielding an indoor L_{Aeq} of approximately 21 dB); and (3) a tilted-window condition (AHP noise filtered to simulate a partially open, tilted window, yielding an indoor L_{Aeq} of approximately 30 dB). Consecutive experimental nights were separated by a minimum of one week. All participants and PSG scoring technicians were blinded to condition assignment on each night.

The acoustic stimuli were derived from outdoor field recordings of a standard 11.2 kW residential AHP unit. Recordings captured the following operationally representative conditions: start-up, continuous steady-state fan-compressor operation, ice formation on the outdoor evaporator and defrost, as well as cleaning cycles, and shut-down. A representative 1-hour acoustic scenario incorporating these modes was constructed and repeated in a loop across the full 8-hour sleep period. Spectral filtering and level adjustments were applied to simulate the frequency-dependent sound insulation for the two experimental 'window position' conditions (tilted vs. closed windows). Loudspeaker playback was calibrated in an unoccupied bedroom to verify that target indoor levels were achieved at the measurement position.

Participants

Forty healthy adults (21 women, 19 men; mean age 37.4 ± 14.6 [18 - 64] years) participated in the study. Eligibility required the absence of clinically significant sleep disorders, confirmed by the Insomnia Severity Index (ISI ≤ 7), the Epworth Sleepiness Scale (ESS ≤ 10), and the Pittsburgh Sleep Quality Index (PSQI ≤ 5). Additional exclusion criteria were: current shift work, regular medication affecting sleep or central nervous system arousal, audiometric hearing thresholds outside age-normal limits, and history of cardiovascular or neurological disease. Written informed consent was obtained prior to enrolment. The study was approved by the local ethics committee of the Charité-Universitätsmedizin Berlin, Campus Mitte, under reference EA1/020/20, and registered with the German Clinical Trial Register under the registration number DRKS00035862. The participants received a reimbursement for their participation.

Polysomnography

PSG was recorded continuously for 8 hours per experimental night in accordance with AASM 2020 scoring rules [6]. Sleep stages (Wake, N1, N2, N3, REM) and standard event scoring were performed manually by certified sleep technologists blinded to condition.

The primary sleep parameters for the total night were Sleep Onset Latency (SOL), Total Sleep Time (TST), Sleep Efficiency (SE = TST / time in bed × 100%), REM latency, N3 latency, proportion of sleep stages N1, N2, N3, and REM (in % of TST), and the number of arousals per night (arousals n/night). The event-related sleep parameter was indexed by noise-associated arousals: EEG frequency accelerations of 3–15 seconds duration, identified by scorers as occurring within 90 seconds of a sound event (audible changes in operation modes).

Subjective Sleep Measures

Each participant completed a standardised evening questionnaire assessing pre-sleep state and habitual sleep quality. In the morning following each experimental night, participants completed a post-sleep questionnaire assessing general and noise-related (1) difficulty falling asleep at sleep onset, (2) frequency and disturbance of nocturnal awakenings, and (3) difficulty sleeping in (early awakening and inability to return to sleep). Responses were recorded on rating scales. Sleepiness was assessed with the Karolinska Sleepiness Scale (KSS) [7] both in the evening prior to sleep and in the morning after waking. A within-person delta-KSS score (evening KSS minus morning KSS) was computed as an index of perceived nocturnal recuperation; positive values indicate reduced morning sleepiness relative to the preceding evening.

Statistical Analysis

Statistical analyses were performed in SPSS version 27. Differences in sleep parameters across the three conditions were tested with the Friedman test ($\alpha = 0.05$) with the three conditions as within-subject factors.

RESULTS

Sample Characteristics

All participants completed all three experimental nights; there were no withdrawals or adverse events. Descriptive statistics for screening measures are provided in Table 1.

Table 1: Participant demographic and screening characteristics (N = 40)

Variable	M	SD	Min	Max
BMI	24.2	3.8	19	33
ISI	3.8	2.5	0	10
ESS	5.4	2.7	2	12
PSQI	5.2	3.9	0	17

BMI = Body Mass Index, ESS = Epworth Sleepiness Scale, ISI = Insomnia Severity Index, M = mean, Max = maximum, Min = minimum, N = number, PSQI=Pittsburgh Sleep Quality Index, SD = standard deviation

Sleep parameter for total night periods

No significant condition effects were observed for all sleep parameters reported in Table 2. In sum, these results indicate that AHP noise at the levels examined did not alter the global architecture of sleep during the night.

Table 2: PSG outcomes across the three experimental conditions (N = 40; median, 25th, 75th percentile)

Variable	**Baseline** Med. (P 25, P 75)	**Closed window ($L_{Aeq,i}$ = 21 dB)** Med. (P 25, P 75)	**Tilted window ($L_{Aeq,i}$ = 30 dB)** Med. (P 25, P 75)	**Friedman p-value**
SOL (min)	12.3 (8.4, 23.0)	15.0 (8.0, 27.8)	12.2 (7.2, 32.0)	0.632
TST (min)	418.2 (363.1, 438.5)	405.7 (375.0, 430.2)	408.2 (352.9, 435.8)	0.417
SE (%)	87.1 (75.6, 91.3)	84.5 (78.1, 89.6)	85.0 (73.5, 90.7)	0.333
REM latency (min)	88.2 (73.7, 156.2)	100.2 (74.6, 134.4)	116.5 (73.1, 182.6)	0.139
N3 latency (min)	37.8 (24.4, 55.2)	34.0 (25.9, 55.3)	39.2 (22.6, 60.1)	0.945
N1 (%TST)	11.6 (8.1, 15.2)	10.6 (7.6, 13.5)	11.6 (8.3, 14.2)	0.139
N2 (%TST)	51.7 (48.0, 58.1)	52.7 (48.1, 59.4)	53.0 (47.8, 58.5)	0.975
N3 (%TST)	17.9 (13.5, 22.4)	17.5 (10.7, 24.3)	16.7 (14.3, 23.4)	0.656
REM (%TST)	17.2 (13.6, 20.7)	18.1 (14.4, 20.2)	16.5 (12.3, 20.8)	0.509
No. of arousals	42.5 (29.2, 58.5)	44.0 (32.2, 57.0)	49.0 (30.7, 58.7)	0.696

h = hour, min = minute, P = percentile, p value = level of significance, REM = Rapid Eye Movement, SE = Sleep Efficiency, SOL = Sleep Onset Latency, TST = Total Sleep Time, N1/N2/N3 = proportion of respective sleep stage, $L_{Aeq,i}$ = continuous equivalent sound level, indoor (see also [5])

Noise-Associated Arousals

A significant condition effect was observed for the number of noise-associated arousal in the two nights with different noise conditions. Figure 1 reveals that in the tilted-window condition (with higher indoor noise levels) the number of all noise-associated arousals (sum of spontaneous, respiratory, and motoric arousals) as well as the spontaneous noise-associated arousals (with respiratory and motoric arousals excluded) was statistically significantly higher in the night with closed-window condition (with lower indoor noise levels) – for all noise-associated arousals: 7.60 ± 5.90 vs. 5.50 ± 3.60, $p < 0.05$; for spontaneous noise-associated arousals: (3.60 ± 2.90 vs. 2.50 ± 1.90, $p < 0.05$). Subgroup analysis by gender showed that the effect of a higher number of arousals in the tilted-window condition compared to the closed-window condition was significant for females ($p < 0.05$), but not for males.

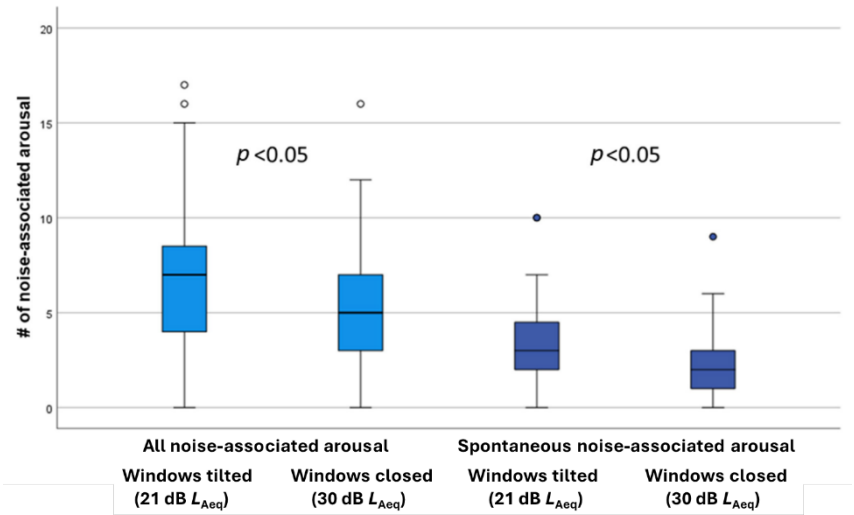

Figure 1: Noise-associated arousals in nights with different noise conditions

Self-reported sleep quality

Absolute morning KSS values did not differ significantly across noise conditions. However, the within-person delta-KSS revealed a meaningful divergence in perceived recuperation. That is, for each night, the difference was calculated between the KSS value assessed in the morning questionnaire after the night and the KSS value in the evening questionnaire before the night, indicating the change in sleepiness in the morning after the night vs. the sleepiness in the evening before the night.

Under the quiet baseline and closed-window conditions, mean sleepiness decreased from evening to morning (baseline: KSS M_{delta} = -0,59; closed window: KSS M_{delta} = -0,62), reflecting the expected restorative outcome of sleep. Under the tilted-window condition, the mean delta-KSS was M_{delta} = +0,32, indicating that participants were sleepier in the morning than in the preceding evening.

In line with this, noise-related sleep disturbance ratings showed significant condition effects (Table 3). In the tilted-window condition, the sleep disturbance when falling asleep, during the night, and when sleeping in was significantly higher than both in the closed-window and the baseline conditions ($p < 0.01$ for all items).

Table 3: Noise-related sleep disturbance in different noise conditions (N = 40)

Noise-related sleep disturbance	**Baseline**			**Closed window ($L_{Aeq,i}$ = 21 dB)**			**Tilted window ($L_{Aeq,i}$ = 30 dB)**			**p-value**
	M	SD	Med.	M	SD	Med.	M	SD	Med.	
when falling asleep	1.72	1.05	1.00	1,69	0.80	2.00	2,78	1.17	3.00	< 0.001
during the night	1.41	0.67	1.00	1.64	0.90	1.00	2.56	1.21	3.00	< 0.001
when sleeping in	1.44	0.72	1.00	1.82	1.10	1.00	2.15	1.14	2.00	< 0.01

Scale from 1 = not at all to 5 = extremely sleep disturbed. M = mean, p = level of significance, SD = standard deviation. Scale from 1 = not at all to 5 = extremely.

DISCUSSION

The central finding of this study is a dissociation between the effects of AHP noise on sleep during the whole night (macrostructure) and the event-related arousal effects (microstructure). Global sleep architecture—total sleep time, sleep efficiency, stage proportions, sleep onset latency, and the total number of arousals did not differ between all three experimental conditions. In contrast, in the tilted-window condition (30 dB $L_{Aeq,indoor}$ the number of noise-associated arousals was higher relative to both the closed-window condition and the quiet baseline – in particular for female persons. The macro-versus-microstructure dissociation observed here is in line with research on the effects of transportation noise on sleep using the PSG approach, e.g. [8]-[9].

Although certain AHP operational events exceeded 33 to 35 dB in A-weighted maximum sound level, which is a level previously associated with the start of noise-induced awakening responses in transportation noise studies [10]-[11], their short duration predominantly elicited arousals rather than full awakenings (i.e., arousals >15 s). This finding suggests that brief noise

events may have limited impact on sleep stage changes and sleep fragmentation as compared to transportation noise. Furthermore, noise-induced alterations in sleep appear to be partially compensated during the night [9]. However, there is evidence that maintaining the macrostructure of sleep throughout the night comes at the biological cost of a lack of restful sleep the following day [12].

The convergence of objective microstructural and subjective outcomes in the tilted-window condition strengthens the internal validity of the findings and their practical relevance. Participants who experienced more noise-associated arousals also reported greater difficulty falling asleep, more sleep disturbance during the night, and greater difficulty sleeping in—all exclusively in the tilted-window condition. In line with this, the delta-KSS findings reveal the failure to achieve the expected morning reduction in subjective sleepiness after the tilted-window night; this implies that the restorative function of sleep was attenuated. In the context of habitual nightly exposure, which can be expected for residents living near AHP installations, such deficits in recuperation could plausibly accumulate to affect daytime alertness, mood, and performance over time, although this cannot be directly concluded from the results of this laboratory study. More research is needed to study the potential aftereffects of exposure to nocturnal AHP noise.

Conclusions based on the findings of this study are limited, first, given that the controlled laboratory environment differs from the home sleep setting. The extent to which these differences moderate the sleep responses to AHP noise cannot be determined from the present data. Second, the sample comprised carefully screened healthy adults without sleep disorders, and the results are likely to underestimate the prevalence and severity of sleep impacts in more vulnerable groups, including older adults, individuals with insomnia or chronic health conditions, and those with heightened noise sensitivity. Third, AHP noise profiles vary considerably by technology type, installation geometry, and seasonal operating conditions, and the generalisability of the specific stimulus used in this study to the full range of residential AHP installations is uncertain. Fourth, the study assessed the acute response to a single night per condition, and no inference can be made about habituation, sensitisation, or the cumulative sleep effects of sustained nightly exposure over weeks or months.

CONCLUSIONS

AHP noise at an indoor level of approximately 30 dB $L_{\mathrm{Aeq,indoor}}$, achieved in this study under sleeping conditions with a simulated bedroom window left in a tilted position, is associated with a statistically significant increase in arousals and impairment of subjective sleep quality in healthy adults. An indoor level of approximately 21 dB(A), achieved in the simulated condition of sleep with the bedroom window being closed, is not associated with significant sleep effect relative to quiet background conditions. The absence of macrostructural disturbance in either noise condition indicates that parameters of the sleep macrostructure are insufficient metrics for detecting the adverse sleep effects of AHP noise; microstructural analysis and standardised subjective sleep disturbance assessment are both required for adequate characterisation.

Future research should employ field-based multi-night study designs in residential areas, examining a range of AHP noise exposure levels emitted by various AHP products across different installation scenarios, as currently deployed in European residential settings.

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Aircraft noise-induced awakenings as a predictor of health effects. A re-analysis of NORAH data

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ABSTRACT

Aircraft noise is one major source of environmental noise and is associated with adverse health effects, such as cardiovascular diseases. To protect residents living near airports from the negative effects of aircraft noise, Germany's Aircraft Noise Protection Act regulates the designation of noise protection zones with the zone for night-time being based on L_{pAeq} and NAT values, within which passive sound insulation is funded. However, there is ongoing debate regarding whether L_{pAeq} and NAT are the most suitable metrics.

A unique approach for designating night-time protection zones around airports has been established at Leipzig/Halle Airport. In a field study conducted by the DLR, the number of aircraft noise induced awakenings was calculated using address-related aircraft noise maximum exposure levels and polysomnographic sleep measurements. Based on these results, new night-time protection zones were designated considering 1 additional awakening and 80 dB L_{Amax}. It remains unclear if and which additional health effects are associated with 1 additional awakening.

To examine this, data of the NORAH (Noise-Related Annoyance, Cognition, and Health) study were enriched with the calculated number of awakenings for each participants' home address. The present analyses are based on data from Frankfurt and Cologne/Bonn Airport collected in 2011 and 2012 with 12,192 participants in total. Participants were randomly selected from the adult population living within the 40-dB L_{pAeq} contours for day- and night-time around each airport. Exposure-response analyses were conducted with the number of additional aircraft noise-induced awakenings investigating their influence on self-reported sleep disturbances, and self-reported diagnoses including hypertension.

INTRODUCTION

Aircraft noise is a major source of environmental noise and has been linked to adverse health outcomes, including sleep disturbances [1] and cardiovascular diseases including

hypertension [2]. In Germany, the Aircraft Noise Protection Act aims to safeguard residents living near airports by defining noise protection zones. The night-time protection zone is based on the metrics L_{pAeq} and NAT, and, among others, residents within these zones are eligible for funding for passive sound insulation measures. However, the suitability of L_{pAeq} and NAT as the most appropriate metrics remains a subject of ongoing debate.

A unique approach to designating night-time protection zones around airports has been implemented at Leipzig/Halle Airport. In a field study conducted by the German Aerospace Center (DLR), the number of aircraft-noise-induced awakenings was assessed using address-specific aircraft noise maximum sound levels in combination with polysomnographic sleep measurements [3]. Based on these findings, new night-time protection zones were established using the criteria of one additional awakening response (AWR) and 80 dB L_{Amax}. However, besides that noise-induced sleep disturbance and fragmentation are in themselves important health effects of environmental noise [1], it remains unclear whether, and to what extent, additional long-term health effects are associated with one additional awakening.

To address this question, data from the NORAH (Noise-Related Annoyance, Cognition, and Health [4]) study were enriched with calculated estimates of the number of awakenings for each participant's residential address.

METHODS

Data sets

The analyses presented here are based on NORAH data collected in 2011 in the Frankfurt and 2012 Cologne/Bonn airports regions, comprising a total sample of 12,192 participants. Participants were randomly selected from the adult population living within the 40-dB L_{pAeq} contours for day- and night-time around both airports. The Frankfurt sample consists of 9,237 participants and the Cologne/Bonn sample of 2,955.

Outcome variables

Sleep disturbance

To assess sleep disturbances due to aircraft noise, participants answered the question "In the last 12 months, how much has aircraft noise disturbed you overall in the following situations: when falling asleep/when sleeping at night/when sleeping off at the end of the sleep period?" using a 5-point scale with 1=*not at all*, 2= *somewhat*, 3=*moderately*, 4=*strongly*, 5=*extremely* disturbed. A mean score was calculated with these three sleep disturbance ratings and participants with a mean score ≥3.67 were categorized as being highly sleep disturbed (HSD). This threshold is equivalent to a cutoff value of 60% of a response scale as defined in ISO/TS 15666 [5] for a person being highly annoyed based on an annoyance assessment on the ICBEN 5-point scale (HA_V).

Hypertension

The 12-month prevalence of hypertension, which was assessed using one item to be answered with yes or no, was used in these analyses.

Exposure metric: Aircraft noise-induced awakenings

For the current study, the NORAH data was enriched with the calculated number of awakenings for each participants' residential address. The formula used to calculate the additional number of awakenings due to aircraft noise is based on the work by [3]. The awakenings were calculated for the scenarios of a tilted and a closed window. For this study, the awakenings calculated for the tilted-window scenario are used as the preferred window position in warmer seasons in Germany.

Other relevant variables

Other relevant factors were considered as well including age, sex, satisfaction with the living environment, satisfaction with the dwelling, socio-economic-status (operationalized as Scheuch-Winkler-Index; SWI; based on education, vocational training, job position, and income), and period of residence.

As there are various individual factors influencing high blood pressure and hypertension, additional confounding factors were considered and controlled for (see also [6]): age, sex, body mass index (BMI), physical activity, alcohol consumption, and noise sensitivity. Physical activity in the last 12 months was assessed with no physical activity in the last 12 months, less than 2 hours per week, 2-4 hours per week, and > 4 hours per week. Participants provided information on their alcohol consumption using the following response categories: don't drink/never, less than 1 drink per day, 1-2 drinks per day, 3-5 drinks per day, and more than 6 drinks per day. Noise sensitivity was assessed using 12 items (NoiSeQ-R) answered on a 4-point scale (1=exactly true, 2=somewhat true, 3=somewhat false, 4=not true at all), of which the mean score was calculated.

Data analyses

First, descriptives including mean, standard deviation, and frequencies were calculated for both the Frankfurt and Cologne/Bonn samples. Correlational analyses using Pearson's r were then performed examining the relationship between sleep disturbance, the calculated additional awakenings (AWR), and other relevant variables.

To analyse the calculated aircraft-noise related additional awakenings' influence on the probability of being highly sleep disturbed (%HSD) and the 12-month prevalence of hypertension, respectively, exposure-response analyses were conducted. IBM SPSS Statistics version 31.0 (IBM Deutschland GmbH, Ehningen, Germany), and R were used for the statistical analyses.

RESULTS

Sample description

The present analyses are based on data from Frankfurt and Cologne/Bonn Airport collected in 2011 with 12,192 participants in total. Thereof, 9,237 are from the Frankfurt Airport region and 2,955 from the Cologne/Bonn Airport region. Table 1 and Table 2 show the sample descriptives. Between approx. 85 % and 87 % of the participants participated via telephone, the others filled in the same questionnaire online. The sex ratio was similar for both airport regions with 53.1 % and 51.5 % being female in the Frankfurt and Cologne/Bonn sample, respectively. In most cases, participants' sex was assessed by the interviewer.

Mean age differs between both airport regions: on average, participants from the Frankfurt Airport region are 49 years of age (SD=15.76). The mean age for the Cologne/Bonn sample is 59 years (SD=16.19). Overall, participants are satisfied with both the living environment and their dwelling, although the Cologne/Bonn sample reports slightly higher satisfaction. Average sleep disturbance ratings are similar between the two samples (FRA: M=2.25, SD=1.31; CGN: M=2.27, SD=1.32).

Table 1: Sample description

Variable		FRA		CGN	
		N	%	N	%
Sex	male	4334	46.9	1433	48.5
	female	4903	53.1	1522	51.5
Mode	telephone	7811	84.6	2583	87.4
	online	1426	15.4	372	12.6
Age groups	< 30 years	1173	12.7	222	7.5
	30-50	3628	39.3	544	18.4
	50-70	3235	35.0	1277	43.2
	≥ 70 years	1201	13.0	909	30.8
	missing	-	-	3	0.1
SWI	Low	1302	14.1	512	17.3
	middle	3966	42.9	1367	46.3
	high	3735	40.4	975	33.0
	missing	234	2.5	101	3.4
Physical activity past 12 months	None	1322	14.3	724	24.5
	<2hrs per week	1267	13.7	525	17.8
	2-4hrs per week	2617	28.3	947	32.0
	>4hrs per week	1850	20.0	740	25.0
	missing	2181	23.6	19	0.6
Alcohol consumption	Never	1353	14.6	696	23.6
	<1 drink per day	4368	47.3	1569	53.1
	1-2 drinks per day	1439	15.6	526	17.8
	3-5 drinks per day	207	2.2	114	3.9
	>6 drinks per day	12	0.1	10	0.3
	missing	1858	20.1	40	1.4
Hypertension	No	5387	58.3	1877	63.5
	Yes	1970	21.3	1031	34.9
	missing	1880	20.4	47	1.6

Table 2: Sample description

	Frankfurt Airport region					Cologne/Bonn Airport region				
Variable	**N**	**Min**	**Max**	**M**	**SD**	**N**	**Min**	**Max**	**M**	**SD**
Age	9237	18	96	49.46	15.76	2952	18	95	58.68	16.19
Period of residence	7444	0	88	23.98	17.90	2954	0	86	23.42	14.95
Satisfaction with living environment	9223	1	5	3.95	1.00	2955	1	5	4.18	0.94
Satisfaction with dwelling	9222	1	5	4.35	0.85	2955	1	5	4.50	0.76
BMI	7210	14.52	56.69	25.19	4.17	2838	14.69	57.76	25.82	4.44
Noise sensitivity	9198	0.00	3.00	1.47	0.97	249	0.00	3.00	1.64	0.68
Sleep disturbance	9225	1	5	2.25	1.31	2951	1	5	2.27	1.32
AWR	9237	0.02	3.52	0.57	0.55	2692	0.00	2.88	0.76	0.63

Correlation analyses

Correlation analyses were performed using Pearson's *r* for both samples separately to assess the relationships between the variables. Results are shown in Table 3 and 4. Significant correlations are found between the average sleep disturbance due to aircraft noise and AWR (FRA: r=.36, p<0.01; CGN: r=.35, p<0.01) in both samples. The AWR are significantly negatively associated with people's satisfaction with their living environment (FRA: r=-.16, p<0.01; CGN: r=-.12, p<0.01). People who are more satisfied with their living environment rate their satisfaction with their dwelling as higher (FRA: r=.37, p<0.01; CGN: r=.38, p<0.01) and report significantly less sleep disturbances (FRA: r=-.26, p<0.01; CGN: r=-.25, p<0.01).

Table 3: Correlation analysis for the Frankfurt Airport sample (N=9,237)

Variable	**Age**	**Period of residence**	**SWI**	**BMI**	**Noise sensitivity**	**Alcohol consump.**	**Physical activity**	**Satisfaction living environ-ment**	**Satisfaction dwelling**	**Sleep distur-bance**
Period of residence	.551**	1								
SWI	.004	-.195**	1							
BMI	.208**	.161**	-.078**	1						
Noise sensitivity	.018	-.040**	.076**	-.071**	1					
Alcohol consumption	.161**	.058**	.164**	.028*	-.021	1				
Physical activity	-.086**	-.032**	.089**	-.171**	.029*	.052**	1			
Satisfaction with living environment	.000	-.024*	.079**	-.012	-.192**	.059**	.020	1		
Satisfaction with dwelling	.134**	.096**	.095**	-.010	-.080**	.054**	.040**	.370**	1	
Sleep disturbance	.089**	.055**	.085**	.022	.327**	-.011	.040**	-.262**	-.034**	1
AWR tilted window	.104**	.205**	-.081**	.098**	.026*	-.034**	-.025*	-.165**	-.023*	.359**

Table 4: Correlation analysis for the Cologne/Bonn Airport sample (N=2,955)

Variable	Age	Period of residence	SWI	BMI	Noise sensitivity	Alcohol consump.	Physical activity	Satisfaction living environ-ment	Satisfaction dwelling	Sleep distur-bance
Period of residence	.531**	1								
SWI	-.084**	-.129**	1							
BMI	.146**	.061**	-.085**	1						
Noise sensitivity	.066**	.007	.105**	-.110**	1					
Alcohol consumption	.060**	.014	.181**	.007	-.005	1				
Physical activity	-.161**	-.095**	.178**	-.143**	.064**	.040*	1			
Satisfaction with living environment	-.010	.010	.096**	-.055**	-.207**	.055**	.035	1		
Satisfaction with dwelling	.072**	.078**	.090**	-.036	-.115**	.014	.054**	.382**	1	
Sleep disturbance	.051**	.014	.090**	.037*	.403**	-.020	.073**	-.254**	-.070**	1
AWR tilted window	.020	.041*	-.063**	.050*	.007	-.012	-.030	-.118**	-.006	.346**

Exposure-response relationships

To assess the impact of AWR's on %HSD and hypertension, exposure-response relationships were calculated separately for both samples. For %HSD, survey mode, age, and sex were added as predictors. For hypertension, additional factors, which are known to influence blood pressure and hypertension, were included as well: age, sex, noise sensitivity, physical activity, alcohol consumption, and BMI. Results are shown in Tables 5 to 8.

In both samples, all predictors have a significant influence on being highly sleep disturbed. For example, for each additional AWR, the probability of being highly sleep disturbed is significantly associated with a 2.93-fold increase (CI: 2.67-3.22) in the Frankfurt sample and with a 2.70-fold increase (CI: 2.33-3.15) in the Cologne/Bonn sample. In the Frankfurt sample, women have approx. 15% higher odds being highly sleep disturbed compared to men. These odds are even higher in the Cologne/Bonn sample with an OR of 27%. The smallest significant effects can be found for age.

Table 5: Results of logistic regression for %HSD based on AWR for Frankfurt Airport sample

Variable	estimate	SE	z	p-value	OR	lower OR	upper OR
(Intercept)	-2.959	0.116	-25.457	0.000	0.052	0.041	0.065
AWR	1.075	0.048	22.586	0.000	2.931	2.670	3.218
Mode: online	0.534	0.078	6.828	0.000	1.706	1.464	1.989
Age	0.008	0.002	4.409	0.000	1.008	1.005	1.012
Sex: female	0.143	0.059	2.431	0.015	1.154	1.028	1.295

Table 6: Results of logistic regression for %HSD based on AWR for Cologne/Bonn Airport sample

Variable	estimate	SE	z	p-value	OR	lower OR	upper OR
(Intercept)	-3.149	0.246	-12.801	0.000	0.043	0.026	0.069
AWR	0.996	0.078	12.844	0.000	2.707	2.325	3.151
Mode: online	0.567	0.152	3.743	0.000	1.763	1.310	2.373
Age	0.007	0.004	1.996	0.046	1.007	1.000	1.014
Sex: female	0.266	0.110	2.415	0.016	1.304	1.051	1.618

Figures 1 and 2 show the exposure-response curves for %HSD for Frankfurt and Cologne/Bonn Airport, respectively. The Frankfurt curve is somewhat steeper than the Cologne/Bonn curve. If on an average night, aircraft noise causes one additional AWR, approx. 20% of the residents will be highly sleep disturbed. According to the WHO, 3%HSD should not be exceeded to avoid substantial negative health effects [7]. The figures show that an increase by 1 AWR is linked to a doubling of %HSD.

The confidence interval for the Cologne/Bonn sample is somewhat wider; this could be due to the smaller sample size for the Cologne/Bonn Airport region.

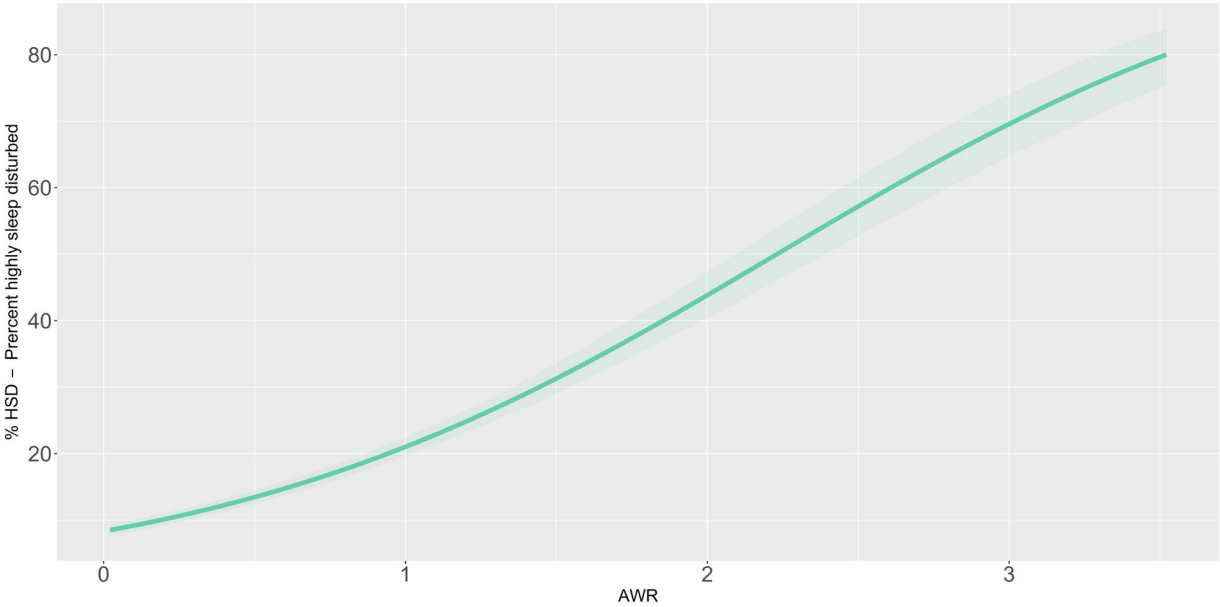

Figure 1: Exposure-response curve for %HSD with AWR for Frankfurt Airport

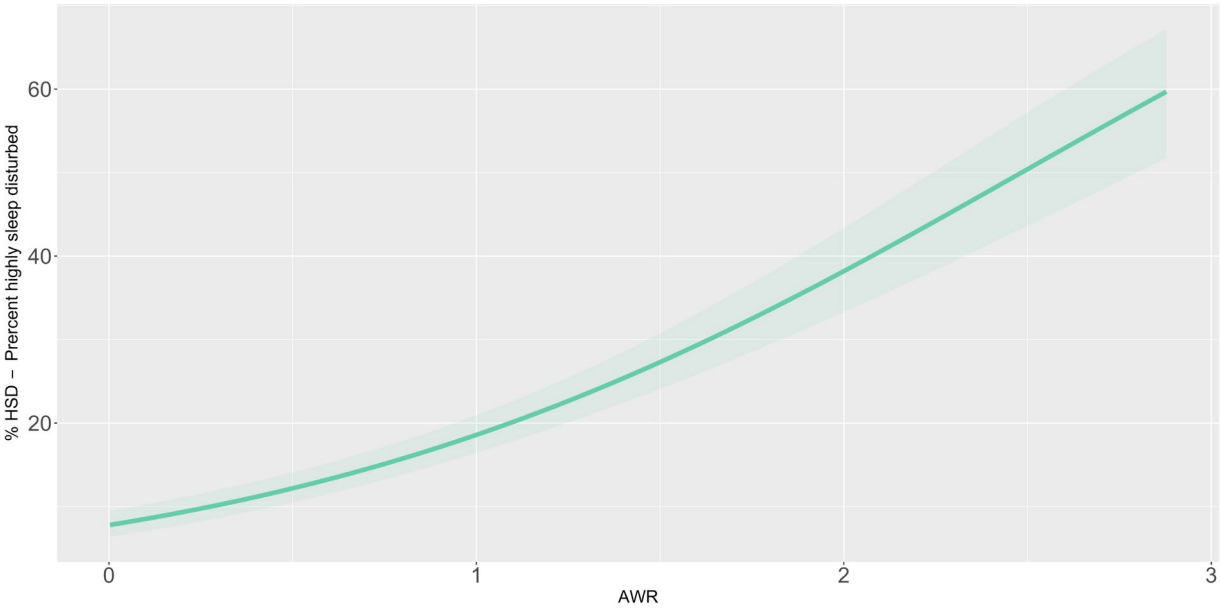

Figure 2: Exposure-response curve for %HSD with AWR for Cologne/Bonn Airport

Results for hypertension are depicted in Tables 7 and 8. AWR have a significant influence on the probability of the 12-month prevalence of hypertension in the Cologne/Bonn Airport sample, but not in the Frankfurt Airport sample.

In both samples, age, BMI and noise sensitivity significantly influence the probability of the 12-month prevalence of hypertension. For example, the odds of a 12-month prevalence of hypertension are 17% higher per BMI increase in the Frankfurt Airport sample and 14% higher in the Cologne/Bonn Airport sample.

Table 7: Results of logistic regression for hypertension based on AWR for Frankfurt Airport sample

Variable	**estimate**	**SE**	**z**	**p-value**	**OR**	**lower OR**	**upper OR**
(Intercept)	-9.290	0.325	-28.613	0.000	0.000	0.000	0.000
AWR	0.086	0.055	1.580	0.114	1.090	0.980	1.213
Age	0.069	0.002	27.684	0.000	1.071	1.066	1.077
Sex: female	-0.131	0.067	-1.956	0.050	0.877	0.770	1.000
BMI	0.171	0.008	20.545	0.000	1.186	1.167	1.206
Physical activity	-0.040	0.030	-1.324	0.185	0.961	0.906	1.019
Alcohol consumption	0.013	0.045	0.295	0.768	1.013	0.928	1.106
Noise sensitivity	0.141	0.033	4.294	0.000	1.152	1.080	1.229

Table 8: Results of logistic regression for hypertension based on AWR for Cologne/Bonn Airport sample

Variable	estimate	SE	z	p-value	OR	lower OR	upper OR
(Intercept)	-8.735	0.519	-16.820	0.000	0.000	0.000	0.000
AWR	0.217	0.075	2.903	0.004	1.243	1.073	1.439
Age	0.067	0.004	17.323	0.000	1.069	1.061	1.078
Sex: female	-0.139	0.099	-1.408	0.159	0.870	0.717	1.056
BMI	0.141	0.012	11.823	0.000	1.151	1.125	1.179
Physical activity	0.029	0.043	0.674	0.500	1.029	0.946	1.120
Alcohol consumption	-0.078	0.061	-1.289	0.197	0.925	0.821	1.041
Noise sensitivity	0.166	0.071	2.340	0.019	1.181	1.027	1.357

Figure 3 depicts the exposure-response curves for the risk increase of a 12-months prevalence of hypertension with AWR for both Frankfurt and Cologne/Bonn Airport with a reference of 0 AWR. The curve for Cologne/Bonn Airport is much steeper than the Frankfurt Airport curve. The risk of hypertension increases from approx. 25% for 1 AWR more than 50% for 2 AWRs and to 90% for 3 AWRs in the Cologne/Bonn sample. In comparison, the risk of 12-months prevalence of hypertension increases by 10 % per one increase in AWR in the Frankfurt sample.

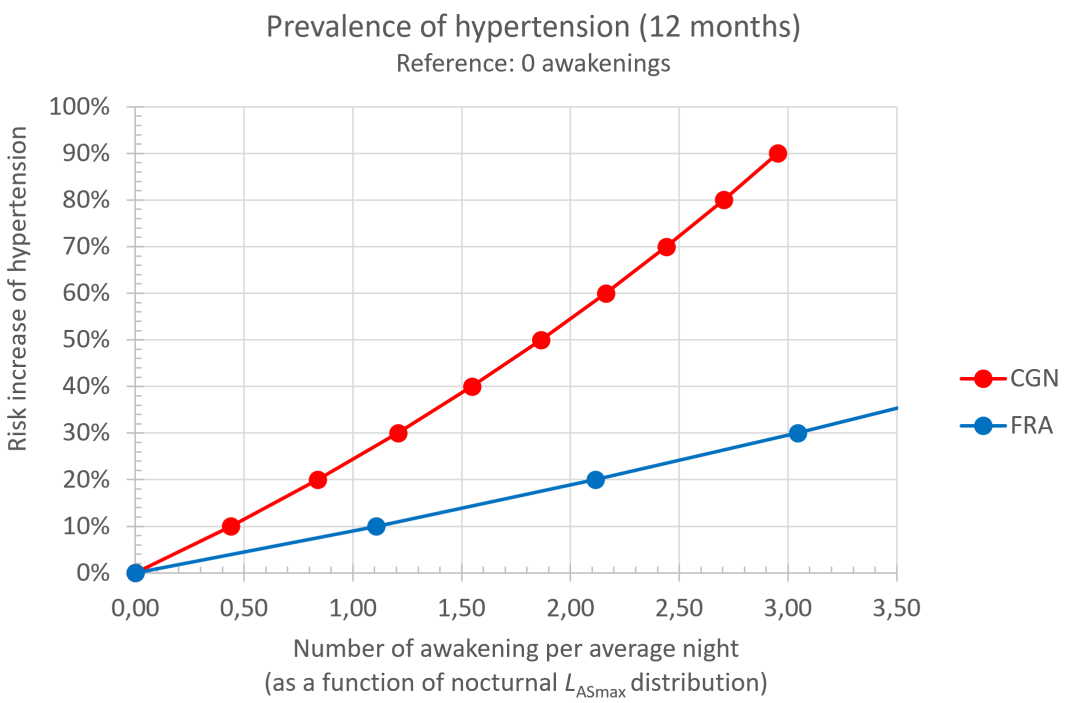

Figure 3: Exposure-response curves for the risk increase of hypertension with AWR for Frankfurt Airport and Cologne/Bonn Airport

DISCUSSION AND CONCLUSIONS

In this contribution, a re-analysis of NORAH data was conducted to assess the impact of calculated additional aircraft noise-induced awakenings on %HSD and the 12-month prevalence of hypertension. Results for %HSD show similar exposure-response curves for both samples, although the curve for Frankfurt Airport is somewhat steeper than the Cologne/Bonn curve. AWR, age, sex, and survey mode all significantly influence the probability of being highly sleep disturbed.

Regarding the prevalence of 12-month hypertension, AWR has only a significant influence in the Cologne/Bonn sample, but not in the Frankfurt sample. Age, BMI, and noise sensitivity significantly influence the prevalence of 12-month hypertension in both samples. The exposure-response curve showing the risk increase of 12-month hypertension is much steeper in the Cologne/Bonn sample. In the Cologne/Bonn sample, the mean AWRs are somewhat higher than in the Frankfurt sample (see Table 2). In addition, the proportion of night flights, as a percentage of the total number of flight movements over a 24-hour period, is higher at Cologne/Bonn Airport than at Frankfurt Airport. For example, there were 115,805 flight movements at Cologne/Bonn Airport in 2013, of which 29.6% were during the night. In 2011, there were 481,585 flight movements in total at Frankfurt Airport with approx. 10% happening during the night.

In conclusion, results regarding %HSD are quite similar for both airports. For hypertension, there seem to be other factors, maybe local circumstances, that affect the results as well. This is a first preliminary step towards research on the long-term health impacts of noise-induced awakenings. Future analyses are needed including other health outcomes (e.g. mental health) and further assessment methods for the health outcomes of interest.

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Team 6 review of community response research published from 2023 to 2025

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ABSTRACT

The central questions in community noise research are: how does noise exposure affect people, what noise characteristics are harmful, and what effects of noise respond to intervention? Within the International Commission on Biological Effects of Noise (ICBEN), Team 6 addresses human responses to environmental noise at the individual and community levels, using noise annoyance as the primary assessment metric. This review synthesizes community response research published from 2023 to 2025, restricted to the Team 6 scope to minimize overlap with other teams. Publications were identified through searches of PubMed, ScienceDirect, and Scopus, and supplemented by publications suggested by members of Team 6. After screening and eligibility assessment, 72 peer-reviewed studies were included and organized by noise source: road traffic, railway, aircraft, wind turbines, occupational settings, and mixed environments. Across noise sources, annoyance is multidimensional and only partly explained by sound level. Non-acoustic factors often match or exceed acoustic variables in explanatory power, especially noise sensitivity, attitudes, perceived fairness and transparency of planning, trust, coping behaviors, and environmental context. Short-term annoyance, which includes reactions from immediate to next-day, is increasingly linked to abrupt changes in noise. Long-term annoyance, or chronic annoyance resulting from noise exposure over weeks, months, or years, appears more strongly shaped by expectations and psychosocial factors. The results point to several research priorities, such as greater understanding of long-term and short-term annoyance processes and the relationships among them, and improved assessment measures.

Keywords: Environmental noise, Annoyance, Community response, Noise sensitivity, Non-acoustic factors, Public health

INTRODUCTION

The most basic question for community noise research is: How does noise exposure affect people? Some key related questions include: How do we accurately assess noise exposure? How do we accurately assess its effects on people? Eventually, community noise research seeks to determine: Which characteristics of noise, including level, are harmful and which are acceptable? Which strategies are most effective for reducing noise-induced effects? The International Commission on Biological Effects of Noise (ICBEN) seeks to promote a high

level of scientific research concerning all the aspects of noise-induced effects on human beings and on animals. ICBEN is divided into nine teams that address the distinct, but interrelated effects of noise. Team 6 research concerns how people respond to noise. The generally agreed-upon metric for assessment is noise annoyance, a construct that describes how much a person is bothered or disturbed by a noise[1]. Community noise research is generally conducted via public surveys or in laboratories. Team 6 also addresses the effects of noise on health-related quality of life.

The goal of this paper is to review new research on community response to noise published from 2023 to the second quarter of 2025. Community response research interrelates with research topics of other ICBEN Teams. Sleep disturbance from noise, for example, is the focus of Team 5. Non-auditory effects of noise, such as health effects, are the focus of Team 3. Low frequency noise and vibration are the focus of Team 7. The current review focuses on research that falls specifically under community response to minimize overlap with the topics of other teams, although in some cases there may be some overlap when we feel that Team 6 can learn from other results. Beyond community response to noise, the scope of the review also includes noise annoyance and effects of noise on health-related quality of life.

An early seminal paper in community noise research was Schultz's 1978 "Synthesis of social surveys on noise annoyance," which put the relationship between noise exposure and community response into a unified framework, regardless of noise source[2]. A decade after Schultz's synthesis, Job systematically explored many factors beyond noise exposure expected to influence human response to noise exposure[3]. Within another decade Miedema and Vos had refined Schultz's curve by showing that the relationship between noise annoyance and noise exposure varied with noise source[4]. At the same time, Fields and ICBEN Team 6 standardized noise reaction survey questions across languages to yield internationally comparables measures of reactions to noise sources[5,6]. In the decades since, community noise research has become more widespread with research originating in more countries and addressing more complex noise sources and more sophisticated models.

Some of the previous Team 6 review papers were published as peer-reviewed journal articles. For example, a paper from 2002 focused on establishing a basis for good sound environments, as opposed to merely acceptable ones, and establishing methods to predict and assess noise annoyance in multi-source environments[7]. Another paper from 2014 called for more studies on cross-cultural comparisons and the community response to noise in developing countries[8]. Studies on both of these topics appear in the current review paper.

Community noise research findings inform technical standards and guidelines. The most well-known set of environmental noise guidelines is the World Health Organization (WHO) Environmental noise guidelines for the European Region, published in 2018[9]. The most relevant technical specification and standard are ISO/TS 15666:2021 Acoustics — Assessment of noise annoyance by means of social and socio-acoustic surveys[1] and ISO 1996-1:2016 Acoustics – Description, measurement and assessment of environmental noise – Part 1: Basic quantities and assessment procedures[10]. Familiarity with these standards and guidelines is considered fundamental to community noise research.

METHODS

We identified publications to include in this review via the following three databases: PubMed, ScienceDirect, and Scopus. To qualify for inclusion, publications were required to be relevant to ICBEN Team 6, peer-reviewed, written in English, and published in the years 2023-2025. The final search queries for each database are shown in Appendix A.

As shown in Figure 1, the initial identification yielded a total of 2202 records from all three databases. We used Endnote to identify duplicates, of which there were 166. Removing the duplicates resulted in 2036 unique publications.

Of the 2036 publications, we excluded 1907 publications that were either out of scope or could not be located. For example, publications were considered out of scope if they did not address community response or annoyance related to a noise problem. We excluded two publications because we were unable to locate the manuscripts. After excluding the out-of-scope publications and the publications that could not be located, a total of 129 publications remained.

At our invitation, members of ICBEN Team 6 reviewed this list of 129 publications and identified an additional 10 publications for consideration. This brought the total number to 139 publications.

Of the 139 publications assessed for eligibility, 67 publications were ultimately excluded from the review. Of those excluded, 38 publications were considered more related to other ICBEN Teams, especially Team 3 (Non-auditory effects of noise), Team 5 (Effects of noise on sleep), and Team 7 (Low frequency noise and vibration). An additional 13 publications were excluded because they did not collect or analyze human response data. Also, eight additional publications were excluded because annoyance was not the primary outcome or objective. There were seven references eliminated for lack of peer review. Finally, one publication was excluded because it analyzed community response data without quantifying the noise dose. In the end, 72 publications were considered eligible and included in the review. These 72 publications are listed in Appendix B.

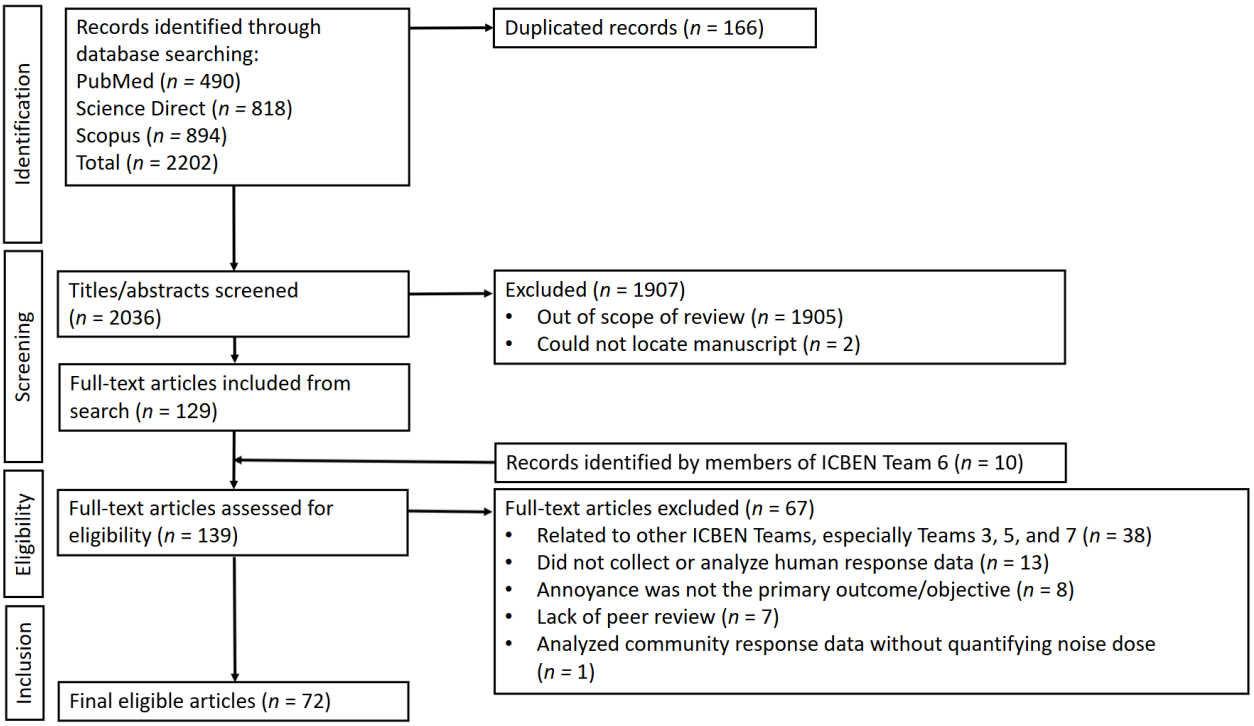

Figure 1: Flow diagram of systematic literature search

RESULTS

Road Traffic—Community Response is multidimensional

To answer how communities react to road traffic noise, various approaches were applied including social surveys, field studies, soundscape assessments, and participatory approaches. Population-based survey evidence further highlights source- and context-dependent differences in annoyance responses. A re-analysis of national data from Germany showed that road traffic noise elicited higher annoyance at lower noise levels than indicated by WHO exposure–response curves, while railway noise annoyance aligned with guideline estimates, underscoring limitations of level-based indicators for characterizing community response to road traffic noise[11]. *Evidence shows that annoyance is shaped far more by non-acoustic factors than by sound level alone.* A 30-year longitudinal investigation of road traffic noise annoyance trends in Bratislava, Slovakia showed a substantial rise at first in road traffic noise annoyance, due to urban development and traffic management changes. The increase in annoyance was later followed by a slight decrease, although annoyance remained a significant concern[12]. Noise-barrier research showed that even 4–12 dBA reductions did not reliably reduce annoyance due to mistrust, expectations, and complaint history[13]. The European FAMOS project confirmed that purely acoustic indicators explain only about one-third of the variance in annoyance[14]. Laboratory work on mixed soundscapes showed reductions in annoyance only when traffic dominance was low and natural sounds were pleasant[15]. Psychoacoustic modeling emphasized the roles of sharpness, loudness, and roughness beyond level-based noise indicators (e.g., L_{Aeq}, L_{den})[16].

Recent field evidence from rapidly urbanizing regions reinforces these findings. A study conducted in Delhi, India demonstrated that prediction models incorporating sociodemographic variables (gender, age, and income), exposure-related variables (exposure duration and daily exposure), and traffic-related parameters (noise level and traffic volume) predicted traffic noise annoyance with good accuracy[17]. Similar patterns were observed in field studies in Thailand[18], where exposure duration, housing setback, and individual sensitivity emerged as dominant predictors. A hybrid deep-learning model integrating spatial feature extraction and temporal sequence learning was developed to predict traffic-induced noise annoyance among 484 participants in Dhanbad, India. The model achieved an accuracy of 93.8% and identified noise sensitivity, honking noise, education level, and sleep disorders as the most influential determinants[19]. However, from a community-response perspective, the practical value of such models depends on their ability to generalize across diverse populations, rather than accurately predicting responses within specific study samples. A recent systematic review which synthesized evidence from 42 studies in China, demonstrated that noise sensitivity, attitudes toward the noise source, health status, perceived environmental quality, and education level play a dominant role in shaping noise annoyance, exceeding the explanatory power of sound level alone[20]. *These findings indicate that accurate prediction of road traffic noise annoyance requires integrative models that combine acoustic indicators with psychological, health-related, and environmental factors, rather than relying on sound level metrics alone.*

Road Traffic—Activity disturbance as an intermediary between exposure and annoyance

Self-reported annoyance, disturbance of daily activities, and subjective evaluations of noise exposure remain essential indicators for understanding the true burden of road traffic noise. In the Zurich, Switzerland RESTORE project (Restorative potential of green spaces in noise-polluted environments), annoyance and perceived stress are examined alongside physiological markers, emphasizing residents' subjective appraisal of noise and greenness[21]. The study conducted in Cox's Bazar City, Bangladesh reported extremely high perceived disturbance

during peak tourism periods, with over 87% of respondents rating the environment as “very” or “extremely noisy” [22]. This result suggests that tourism-driven traffic intensification can push urban sound environments beyond both regulatory limits and subjective tolerance thresholds. Importantly, the significant role of exposure duration and health risk awareness indicates that annoyance is not solely a function of noise intensity but also of cumulative exposure and individual perception. From a community perspective, this implies that managing temporal patterns of exposure may be as important as reducing overall noise levels.

Even when noise levels are moderate, noise sensitivity, nature relatedness[i], and expectations about tranquil environments significantly shape annoyance responses[23]. A field experiment involving a walk through a forest or an urban street randomly assigned a test condition to each participant and assessed them before and after their walk. The results further demonstrated that road traffic noise disrupts subjective restoration and stress recovery, even when physiological measures such as cortisol do not show corresponding changes, underscoring noise as a psychological and activity-related stressor[24].

Similarly, studies on vehicle sound quality indicate that tonal and timbral features associated with truck tire noise can heighten annoyance independently of noise level[25, 26]. A study using crowdsourced cycling data found that while cyclists often downplayed noise as a minor annoyance, they nevertheless modified routes and behaviors to avoid it, indicating that activity disturbance can influence behavior even when annoyance is not explicitly reported as severe[27]. In other words, behavioral adaptation may serve as an additional indicator of community impact, complementing traditional annoyance metrics.

Road Traffic— Annoyance as an exposure pathway to health and well-being

Studies focusing on health-related quality of life consistently show that annoyance integrates repeated activity disturbance, psychological appraisal, and coping capacity, emphasizing its role as more than a simple subjective reaction. A two-stage structural equation modeling–support vector machine study conducted in Riyadh, Saudi Arabia shows that noise sensitivity and subjective noise perception strongly predict annoyance, underscoring its importance in shaping overall quality of life[28]. Large-scale analyses, such as the German NORAH study (Noise Related Annoyance, Cognition and Health), further reveal that environmental context, particularly residential greenery, modulates annoyance responses to different noise sources, thereby influencing perceived well-being[29]. Environmental context therefore acts as a mediating layer between noise exposure and health-related outcomes, rather than a simple background condition.

Importantly, source-specific characteristics of road traffic noise also play a critical role in mediating health effects. Studies focusing on intermittent and spectrally salient components, such as honking and tonal tire noise, demonstrate that these features intensify annoyance and partially mediate adverse psychological health effects[17, 26]. Also, a study employing structural equation modeling combined with an artificial neural network confirms that annoyance induced by honking and other intermittent traffic noise acts as a partial mediator between noise exposure and adverse psychological health effects among exposed workers[30]. Finally, a study of urban intersections in mid-sized Indian cities showed that traffic– noise–induced annoyance is driven primarily by noise sensitivity and honking, with additional effects from exposure duration and acoustic characteristics, and that annoyance partially mediates the relationship between traffic noise exposure and psychological health[31]. From a policy perspective, this result supports the role of annoyance as a meaningful intermediary outcome linking environmental exposure to broader health impacts.

Railway

Evidence from occupational settings suggests that railway noise may pose health risks to workers in enclosed rail environments. A study among Tehran, Iran metro workers found that platform employees experienced higher noise exposure than control room staff, with a subset exceeding permissible limits and showing increased annoyance and early signs of high-frequency hearing effects[32].

Beyond sound level alone, psychoacoustic characteristics of train pass-bys shape perceived disturbance, particularly for high-speed rail systems. A Korean study reported that Doppler-induced frequency shifts, when combined with binaural cues, can reduce annoyance from high-speed train noise, offering insight into the commonly observed "train noise bonus"[33]. This highlights the role of dynamic acoustic features in moderating perceived annoyance beyond energy-based metrics. At the community scale, noise level remains limited in capturing short-term, event-related annoyance.

At the population level, responses to conventional railway noise differ systematically from those to other transport noise sources and are shaped by source-specific acoustic properties. A re-analysis of national survey data from Germany showed that railway noise annoyance followed WHO exposure–response relationships, while sleep disturbance was lower at comparable nighttime noise exposure. By contrast, road traffic noise elicited higher annoyance at lower noise levels, underscoring the importance of noise source and outcome type in railway noise assessment[11]. Source-specific engineering interventions further influence perception: A German laboratory study found that synthesized freight train sounds with low-roughness composite brake blocks were rated as more pleasant than conventional cast-iron brake wagons, with pleasantness increasing as the proportion of retrofitted wagons increased[34].

Aircraft—Fixed Wing

Recent research on fixed-wing aircraft noise challenges simple exposure-response models and demonstrates that annoyance outcomes are shaped by a complex interplay of non-acoustic factors, geographic and cultural variation, and methodological choices. Non-acoustic factors: Even when noise exposure changes, attitudes and contextual factors maintain their impact on annoyance. Residents near Tan Son Nhat airport in Ho Chi Minh City, Vietnam maintained high annoyance during the COVID-19 pandemic despite reduced flight operations[35], while a structural equation model found that non-acoustic variables influenced noise annoyance and insomnia as strongly as acoustic exposure itself[36]. This result suggests that reducing noise levels without addressing attitudes and contextual factors may not yield a proportional reduction in community annoyance. Geographic and cultural variation: Survey results from Leipzig, Germany revealed higher sensitivity to aircraft noise than predicted by WHO exposure-response functions[37], suggesting that local factors or population characteristics may amplify responses beyond international averages. Methodological considerations: Study design choices affect exposure-response relationships. A Bulgarian survey's limited number of observations at high levels of noise exposure may have artificially attenuated the observed relationship, highlighting the need for methodological standards[38]. Observed exposure–response relationships may therefore partly reflect study design limitations rather than representative population-level responses. Also, a Canadian study demonstrated that aircraft noise contours based on average air traffic tend to underestimate severe annoyance, while composite scenarios incorporating both average and worst-case exposures provide substantially better predictions[39].

A pilot survey on community impacts of aviation noise found that respondents experienced stress and negative effects on mental and physical health[40]. Because the results are based on a convenience sample, the findings apply only to the specific sample studied rather than the population at large.

Regarding noise inside the aircraft cabin, loudness and sharpness were identified as the primary drivers of discomfort[41].

Aircraft—Helicopters

Recent helicopter noise research indicates that traditional energy-based acoustic metrics, such as sound exposure level, inadequately capture perceptually significant features. For example, one laboratory study found statistically significant perceptual aspects of helicopter noise, including spectral, temporal, or spatial noise characteristics, that are not accounted for by sound exposure level[42]. Another laboratory study found that annoyance correlates as highly with loudness-based time-integrated noise metrics as it does with more traditional acoustic metrics[43]. Additionally, multilevel analysis showed that annoyance onset thresholds vary more than annoyance growth rates across test subjects[44]. *Collectively, these findings highlight the need for refined assessment tools that incorporate perceptual factors and account for individual differences.*

Aircraft—New Concepts

Recent laboratory studies have examined noise characteristics and annoyance responses for emerging aircraft technologies, revealing both promising noise reduction strategies and new acoustic concerns. One study focused on the blended wing body, an aircraft design resembling a manta ray, in which the extended fuselage provides acoustic shielding from engines mounted above it. This configuration decreased ground-level noise and resulted in reduced short-term annoyance for both takeoff and landing compared with conventional aircraft[45]. However, not all emerging aviation technologies demonstrate noise benefits. Two laboratory studies examined noise annoyance from unmanned aerial systems (UAS), commonly known as drones. The first study revealed higher short-term annoyance toward drones than other transportation noise sources, including fixed-wing aircraft, helicopters, and cars. In terms of drone maneuvers, takeoffs, landings, and slow fly-bys were found more annoying than faster fly-bys[46]. A follow-up study found that annoyance levels varied based on multiple factors, including UAS type, operational mode, sound characteristics, flight frequency, and ambient acoustic environment. Annoyance also appeared associated with personal attitudes toward advanced air mobility technology and residential area classification[47]. No publications were identified regarding noise from passenger and equivalent cargo-carrying advanced air mobility vehicles ("air taxis"), although reviewers of this manuscript did point out at least one reference that was missed. Additional research is expected in the coming years as this technology matures and enters operational testing phases.

Wind turbines

Residents' perceptions of fairness, transparency, and participation in planning consistently emerge as stronger predictors of annoyance to wind turbine noise and acceptance than acoustical measurements alone. A long-term field study showed that fairness in the planning process is the most influential subjective factor associated with annoyance[48]. A study of strongly annoyed residents confirmed that perceived unfairness, property value concerns, and negative attitudes toward the local wind farm drive high annoyance, especially during nighttime exposure[49]. A longitudinal study in Japan further demonstrated that the perceived need for public involvement increases over time and remains strongly linked to annoyance and acceptance, particularly among newer residents[50]. Transparent planning and meaningful community participation are essential for reducing annoyance and improving social acceptance of wind energy projects. Community acceptance is therefore not solely a noise exposure issue, but more fundamentally a social and governance challenge.

Annoyance and unpleasantness from wind turbine and airborne wind energy system (AWES) sounds were consistently associated more highly with acoustic characteristics than with overall noise level. In laboratory settings, annoyance was generally low but increased with prolonged exposure, and was strongly associated with sharpness, loudness, roughness, and fluctuation strength[51]. Long-term field studies showed that noise level and vibration alone could not explain annoyance; instead, amplitude modulation, rotational speed, and wind/weather conditions were more relevant predictors of disturbance[49]. Strongly annoyed residents were distinguished by noise sensitivity and negative perceptions of fairness, not by noise exposure[50]. Regulatory metrics based on sound emergence were poor predictors of short-term annoyance, whereas noise level and loudness performed better[52]. For AWES, sharpness was the only consistent predictor of annoyance at equal noise level, with tonal fixed-wing systems perceived as most unpleasant[53]. Over a decade, annoyance tended to decrease among long-term residents, while newcomers were more disturbed [48]. This trend likely reflects habituation and increased acceptance among long-term residents, whereas newcomers—lacking prior exposure and often holding different expectations—are more sensitive to perceived disturbance. Variations in perceived fairness and pre-existing attitudes toward the project may further contribute to this difference.

Noise in multi-unit residences

Research on noise in multi-unit residences reveals both source-specific patterns of annoyance and an effective mitigation strategy. As a noise source, floor impact noise had the strongest effects on perceived controllability—2 to 4 times greater than other sounds from next-door and from outdoors[54]. Annoyance effects from floor impact noise were significantly influenced by personal factors, such as coping methods and noise sensitivity, and social factors, such as neighbor conflicts and attitudes, rather than by noise level alone[55,56]. Similarly, construction noise annoyance depended more on non-acoustic factors, like perceived safety, noise perception in the bedroom, and construction nuisances, than on the noise levels[57]. A survey study from South Korea found that railway noise was more annoying than road traffic for high-rise residents, contradicting expectations of a railway bonus, possibly due to track proximity, negative attitudes, and vibrations[58]. Regarding impact sound vs. airborne sound, a Canadian survey found that airborne sound insulation and annoyance correlated, whereas impact sound insulation did not significantly correlate with annoyance but rather with activity disturbance[59]. Finally, in terms of mitigation approaches, active-noise-control windows combined with natural sound maskers like bird or water sounds improve acoustic comfort even without substantial reductions in noise level[60].

Occupational Noise

Although occupational noise is traditionally a focus of Team 4 – Effects of noise on performance and behavior, some papers from this topic were included in the review because they involve annoyance and we believe Team 6 can learn from the methods and results. For example, in a questionnaire survey of 542 workers in a steel factory in Iran, more than half reported being annoyed by workplace noise, and nearly half rated loudness as extremely high[61]. Using a Bayesian network to model conditional dependencies among correlated psychosocial and perceptual factors, the study identified job stress, noise sensitivity, and personality traits as stronger predictors of annoyance than noise level alone.

Psychosocial working conditions further modulate the cognitive consequences of noise annoyance. An online survey conducted in Lebanon found that the cognitive impact of noise annoyance depended strongly on work-related psychosocial conditions[62]. Under low effort, low reward, or high overcommitment—conditions similar to stressful occupational environments—

noise annoyance was significantly associated with poorer memory, attention, and processing speed. When psychosocial conditions were more favorable, these negative effects weakened, indicating that stress amplifies the cognitive burden of noise in the workplace.

Targeted workplace interventions can reduce noise-related distraction and improve perceived well-being. A longitudinal field study in open-plan offices demonstrated that level-adaptive sound masking effectively reduced intelligible speech distraction and improved short-term mental health while decreasing reliance on coping behaviors such as headphone use[63]. In clinical environments, an architectural redesign reduced overall noise levels and significantly decreased distractions among nurses, while a reduction in noise from equipment (such as alarms), telephones, and the doorbell further reduced annoyance[64].

Even when regulatory limits are met, occupational noise exposures can remain highly annoying in specialized work settings. Research on noise in ship cabins in China demonstrated that combined noise and vibration could produce substantial annoyance despite compliance with regulatory limits, with noise contributing more strongly to subjective annoyance than vibration, and discomfort increasing sharply when noise levels exceed approximately 57.5 dB(A)[65].

Other—Non-specific noise source

Recent research challenges traditional assumptions about noise exposure-response relationships by revealing how noise annoyance can be context-dependent and dynamic. For example, a study that assessed short-term annoyance via an electronic questionnaire found that short-term annoyance was related to both noise level and noise level increment, or how much louder the current noise was compared with the last several minutes[66]. Also, a lab study found that spectral shape influences short-term annoyance ratings for wide-band, steady state noises, above and beyond noise level, with penalties as high as +12 dB for greater concentration of sound energy in the high frequency range[67].

Another assumption about short-term annoyance is that real-time assessments are equivalent to assessments delayed by several hours, for example at the end of the day. *Research comparing real-time Ecological Momentary Assessment data to recalled data from the Day Reconstruction Method challenges this assumption with the finding that people exhibited greater sensitivity to noise levels in real-time than at the end of the day*[68]. Another analysis of the dataset showed significant effects of temporal (e.g. weekday vs. weekend), spatial (e.g. at home vs. at work vs. somewhere else), and social (e.g. alone vs. with others) variables on noise annoyance, which underscores the role of context in noise annoyance[69].

Other—Multiple noise sources

Transportation noise annoyance cannot be explained via acoustic measures alone, as cultural, demographic, and geographic contexts also influence human response. Research in Germany demonstrates context-specific sensitivity patterns: road traffic noise produces exposure-response curves exceeding international averages—meaning lower noise levels generate greater annoyance than in other countries—while railway noise shows steeper slopes at higher exposures, indicating heightened sensitivity to increases. These patterns hold across urbanization levels after controlling for exposure[11]. Research from the United States suggests profound demographic disparities in noise burden, with racial and ethnic minority populations experiencing disproportionately high annoyance from aviation, rail, and roadway noise while racial majority populations remain consistently less affected[70]. To support more nuanced assessments beyond sound level measurements, researchers have proposed a method for estimating psychoacoustic and noise indices from A-weighted equivalent sound pressure level data[71].

Other—Noise Sensitivity

In many reviewed studies, noise sensitivity explains individual variability in annoyance responses, often matching or exceeding the significance of acoustic indicators such as sound level. Individuals with higher noise sensitivity consistently reported greater annoyance and stronger adverse responses under similar noise exposure conditions across occupational, residential, and urban settings[36]. Noise sensitivity also modifies exposure–response relationships, with more sensitive individuals reacting at lower sound levels and showing steeper, non-linear annoyance gradients in both real-time and recalled assessments[68]. Noise sensitivity is most commonly measured using self-reported psychometric instruments that capture stable individual differences in responsiveness to everyday sounds and are generally treated as trait-like characteristics[15]. Measurement approaches range from single-item questions used in large-scale surveys to standardized multi-item instruments such as the Weinstein Noise Sensitivity Scale, which has demonstrated acceptable reliability across diverse populations[61]. As a result, noise sensitivity is increasingly included as an independent predictor or moderating variable in statistical and machine-learning models, significantly improving annoyance prediction beyond physical noise metrics alone. However, despite being strongly associated with annoyance at the individual level, the utility and relevance of noise sensitivity for community-level noise management may be limited, as policies must address the entire population rather than specific subgroups

Other—Greenery as context-sensitive moderator of noise annoyance

Accumulating evidence suggests that greenery functions primarily as a context-sensitive moderator of noise annoyance, rather than as a direct acoustic mitigation measure. A nationwide Swiss study found a clearer effect for road traffic noise, where increasing residential greenness represented by normalized difference vegetation index was associated with a substantial reduction in annoyance, equivalent to lowering noise by about 4 dB[72]. Experimental and observational studies further demonstrated that visual exposure to vegetation, particularly at intermediate levels of greenness, can reduce indoor and outdoor traffic noise annoyance, while excessively dense vegetation may yield diminishing returns[23]. Virtual reality experiments further showed that road traffic noise annoyance is minimized at an intermediate level of visible greenness, and that aesthetic quality of vegetation—rather than quantity alone—drives this mitigation effect, indicating a perceptual and restorative pathway[73]. Complementary evidence from forest and quiet-area studies indicates that greener environments with higher relative quiet time are associated with increased perceived restorativeness, stress recovery, and comfort, supporting an indirect restorative pathway through which greenery alleviates annoyance[24]. The benefits of greenery are therefore primarily perceptual and contextual rather than acoustical, emphasizing the importance of environmental experience over physical noise reduction.

However, the moderating role of greenery is not universal and exhibits clear non-linearities, varying by sound source and exposure context. Greenery may have limited effectiveness or may even increase annoyance at higher noise levels. Large-scale evidence from the NORAH study shows that greenery's effect on annoyance is source- and context-dependent and follows non-linear patterns: road traffic noise annoyance decreases with increasing greenery at moderate noise exposure but may rise again at higher noise exposure; aircraft noise shows the opposite pattern; and railway noise shows no consistent relationship[29a]. These findings are consistent with earlier evidence from the Swiss SiRENE study (Short and Long Term Effects of Transportation Noise Exposure), which demonstrated systematic differences in exposure–response relationships across transport sources, with greenery reducing annoyance for road and railway noise but increasing it for aircraft noise[29b]. Compared to the more context-dependent

patterns observed in the NORAH study, the SiRENE findings point to a more consistent source-specific influence of greenery. Greenery may enhance the benefits of reduced road traffic exposure while simultaneously increasing sensitivity to aircraft noise due to heightened expectations of tranquility and perceptual incongruence. Annoyance may therefore increase not because of higher noise levels, but because of a mismatch between expected and experienced environments.

Beyond visual mechanisms, soundscape research emphasizes the importance of audio-visual integration, showing that natural sounds combined with green visual contexts can further reduce traffic noise annoyance when traffic dominance is low[23]. Similarly, a virtual-reality-based green-window study demonstrates that participants reported lower annoyance when vegetation was aesthetically pleasing, showing that visual context influences subjective noise evaluations despite constant sound levels[73]. G*reen and forested environments therefore reduce annoyance through perceptual, cognitive, and restorative pathways, rather than through direct sound reduction.*

Other—Methods Development

Recent noise-annoyance research reveals insights about research methods, perceptual mechanisms, and field-wide trends. Methodologically, survey results are strongly influenced by survey-specific factors—question wording, presentation format, response scales, and scoring methods—which challenges survey comparability[74]. In terms of analysis techniques, the Community Tolerance Level method offers a first-principles alternative to regression, requiring fewer assumptions while yielding exposure-response relationships that closely match modern curve fits[75]. From a methodological perspective, soundscape appropriateness has been identified as a mediating variable linking sound source types to perceived acoustic comfort[76.] A comprehensive review of noise annoyance research from 2015–2024 showed a shift in research emphasis from conceptual studies (i.e., studies focused on model development or theoretical frameworks without new empirical data) and survey-based studies toward engineering and applied-acoustics domains with increased experimental and measurement-based approaches. The review also identified: a decline in road-traffic noise studies; notable growth in air-transport noise studies; and emerging interests in urban noise, environmental safety, and noise impacts across different application domains (e.g., transport systems, urban planning, and the built environment)[77].

Recent advances in data-driven modeling show that deep learning can directly map acoustic features to subjective annoyance ratings. A deep learning–based annoyance assessment approach trained on listening experiment data achieved substantially lower prediction error than conventional regression and neural network models, with further improvements obtained through transfer learning, enhancing robustness and correlation between predicted and observed annoyance levels[78]. Recent studies increasingly adopt mobility-based and multisensory approaches to better capture real-world noise perception. A survey with 800 participants in Hong Kong combining GPS trajectories with street-level visual indicators demonstrated that features such as building density, vegetation, sky visibility, and lighting conditions exert non-linear effects on perceived noise, annoyance, and stress[79]. However, even highly accurate models may offer limited practical value until they translate into clear and actionable guidance for community-level noise management.

Other Considerations

Advances in noise annoyance research are refining both how annoyance should be measured and what mechanisms may contribute to it. For example, a laboratory study of individual

annoyance responses showed low between- and within-participant stability, but high stability of mean annoyance values. The study's authors also found that the other sounds included in the experiment influence noise annoyance ratings[80]. Meanwhile, research into unexplained annoyance responses has identified that inaudible infrasound can subtly alter brain network functioning, which may be a cause of annoyance[81]. However, a recent systematic review and meta-analysis evaluating noise annoyance as a determinant of physiological changes linked to disease promotion concluded that the overall certainty of evidence for such biological effects remains very low, largely due to risk of bias, inconsistency, and imprecision across studies[82]. Although some pooled estimates suggest possible associations between annoyance and biomarkers, current evidence does not robustly support annoyance as a direct precursor to chronic physical disease.

While recent studies demonstrate increasing methodological sophistication, their implications for community response are not always clear. Many findings emphasize subgroup differences or statistically significant relationships that may have limited relevance for real-world noise management. From a community perspective, the key challenge is to translate these findings into insights that reflect the experience of the overall population, rather than specific or highly controlled study conditions.

OBSERVATIONS / CHALLENGES / OPPORTUNITIES

Across all noise sources reviewed—road traffic, railway, aircraft, wind turbines, occupational settings, and mixed environments—several unifying observations emerge regarding persistent challenges and promising opportunities for advancing community-response research.

Increasing specificity of receiver groups and implications for comparability

Recent studies target cyclists, adolescents, nurses, metro workers, office employees, and residents in unique environmental contexts, revealing that annoyance is highly dependent on situational, psychosocial, and environmental conditions. This specificity improves ecological validity but also increases methodological fragmentation and limits comparability across studies[27,32,61,63,64]. From a community-response perspective, such subgroup-specific findings may have limited generalizability for policy-making, which must address heterogeneous populations rather than isolated groups. Future research should therefore emphasize how to integrate subgroup-specific findings into more general principles as a basis for noise policies. An important priority is to standardize annoyance measures (e.g., question wording, response scales, recall periods, and "highly annoyed" thresholds) and subgroup-specific exposure–response functions while preserving contextual detail[74].

Noise sensitivity as a dominant moderator of annoyance

Noise sensitivity consistently appears as one of the strongest moderators of annoyance across all source types—from Delhi road traffic to Thai urban noise, from ship cabins to steel factories, and in psychoacoustic laboratory tests[17,18,61,65,36]. Yet measurement tools differ widely, and sensitivity is often inconsistently operationalized. Although noise sensitivity explains individual variability, its relevance for community-level policy remains limited, as population composition cannot be controlled in practice. *Developing a unified, reliable, and economical noise-sensitivity instrument is therefore a major research priority*[61,74].

Distinguishing short-term and long-term annoyance processes

Evidence increasingly distinguishes short-term annoyance, driven by suddenness, temporal variation, and eventfulness (e.g., honking, sound increments, Doppler shifts), from long-term annoyance shaped by chronic exposure, fairness perceptions, attitudes, expectations, and environmental context[66,68,69,33,48]. Momentary annoyance is influenced by non-stationarity and abrupt changes, while long-term annoyance integrates health perceptions, sleep disturbance, and psychological stress. This distinction suggests that different mitigation strategies may be required for short-term and long-term annoyance, rather than treating annoyance as a single unified outcome. Furthermore, advances in experience sampling methods (e.g., railway ESM, cycling GPS–noise diaries) offer an opportunity to link these temporal layers[27,68,69].

Multi-sensory and environmental modifiers of annoyance

Multi-sensory and environmental modifiers, including greenery, visual context, urban form, and vibration, are shown to meaningfully alter annoyance responses even at constant noise levels [23, 24, 65, 79]. Greenery reduces road-traffic annoyance (Zurich, Switzerland), has mixed effects for aircraft (NORAH), and has minimally consistent effects for rail [29, 72, 73]. Visual appropriateness, aesthetic quality, and sky–plant proportions also mediate annoyance, underscoring the need for integrated audio–visual exposure frameworks [73, 76].

Underrepresentation of non-acoustic factors in policy and regulation:

Non-acoustic factors such as fairness, trust, planning transparency, coping behaviors, and perceived controllability often show equal or greater influence on annoyance than sound levels, particularly for aircraft and wind turbine noise [36, 48, 49, 50, 55, 56]. A gap therefore exists between scientific evidence and current regulatory practice, because policies remain largely based on acoustic indicators alone. These observations suggest that advancing community noise policy requires a shift beyond purely exposure-based models toward integrative frameworks that incorporate temporal dynamics, multisensory context, and variability in responses across individuals within the community.

Status and importance of the ISAR Archive (https://www.icben.org/isar/)

The ICBEN Socio-Acoustic Survey Archive (ISAR), currently under development, is a specialized repository designed to collect, store, and share original data from noise surveys. Its primary purpose is to facilitate cross-cultural, longitudinal, and pooled analyses of noise effects—specifically annoyance and noise-induced sleep disturbance—to inform noise policies and improve, standardize, or update environmental noise guidelines. The ISAR archive represents a critical infrastructure for future progress in the discipline of noise effects research and will be made available to everyone on the Zenodo open data platform. Although compilation is slow and dependent on voluntary data sharing, the first release of the archive is planned once about 20 studies are assembled. Over the past two years, the applicable general terms and conditions have been drawn up, comprehensive legal consultations on relevant data protection issues have been conducted, and, above all, attempts have been made to convince the authors of earlier surveys to make their data available for the archive. Unfortunately, in some cases, this has not been very successful and remains a laborious ongoing process. Despite this, the preliminary (unpublished) archive version already holds more than 100,000 individual records of noise exposure-response data. Encouraging the ICBEN Team 6 members and other peers in the field to contribute their data remains essential to achieve the objective of establishing the ISAR archive as a relevant tool for the entire noise effects research community.

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APPENDIX A – SEARCH QUERIES

PubMed

(("noise"[tiab] OR "sound"[tiab] OR "dB"[tiab]) AND ("response"[tiab] AND ("annoyance"[tiab] OR "disturbance"[tiab] OR "health"[tiab] OR "quality of life"[tiab])) AND 2023/01/01:2025/12/31[Date - Publication]) AND (english[Filter])

ScienceDirect

Results were combined from the following three queries:

("noise" OR "sound") AND "community" AND "dB" AND "annoyance" AND "response" AND ("disturbance" OR "health" OR "quality of life")

("noise" OR "sound" OR “dB”) AND "community response" AND ("annoyance" OR "disturbance" OR "health" OR "quality of life")

("noise" OR "sound") AND "dB" AND "annoyance" AND "response" AND ("disturbance" OR "health" OR "quality of life")

Scopus

Results were combined from the following three queries:

("noise" OR "sound") AND "community" AND "dB" AND "annoyance" AND "response" AND ("disturbance" OR "health" OR "quality of life")

("noise" OR "sound" OR “dB”) AND "community response" AND ("annoyance" OR "disturbance" OR "health" OR "quality of life")

("noise" OR "sound") AND "dB" AND "annoyance" AND "response" AND ("disturbance" OR "health" OR "quality of life")

APPENDIX B – TABLE OF REVIEWED STUDIES*

*References 1 – 10 are not included in this table because they are background references and not among the 72 studies that met the eligibility criteria for inclusion in this review.

Ref No.	Author, Year	Country	Noise Source	Research context
11	Benz, et al. 2025	Germany	Road, rail	Indoor, residential, rural, suburban, urban, field survey
12	Argalasova, et al. 2025	Slovakia	Road	Outdoor, urban, field survey
13	Barros, et al. 2024	Belgium	Road	Outdoor, residential, suburban, field survey
14	Bendtsen, et al. 2023	Norway/Europe	Road	Outdoor, residential, urban, literature review, field survey, laboratory
15	Chau, et al. 2023	Hong Kong, China	Road	Indoor, controlled listening environment, effect of birdsong and water sounds
16	Chudalla, et al. 2023	Germany	Road	Outdoor, urban, field survey
17	Mann, et al. 2024	India	Road	outdoor urban intersections, field survey
18	Siwapathomchai, et al. 2023	Thailand	Road	Indoor, residential, suburban, field survey
19	Tiwari, et al 2023	India	Road	Outdoor, urban, field survey
20	Wang, et al. 2025	China	General	Review paper
21	Dopico, et al. 2023	Switzerland	Road	Outdoor, residential, urban, field survey
22	Nath, et al. 2024	Bangladesh	Road	Outdoor, workplace, major road intersections, workers, field
23	Pasanen, et al. 2025	Finland	Road	Outdoor, residential, field survey
24	Schaupp, et al. 2025	Switzerland	Road	Outdoor, urban and forests, field survey

Ref No.	Author, Year	Country	Noise Source	Research context
25	Marin-Cudraz, et al. 2024	France	Tire	Controlled listening environment
26	Parizet, et al. 2025	France	Tire	Outdoor, urban, field survey
27	Wogan and Kennedy, 2024	Ireland	Road	Outdoor, cyclists, urban, field survey
28	Rehman, et al. 2024	Saudi Arabia	Road	General, commercial and residential, field survey and methods development
29	Schaffer, et al. 2025	Germany	Road, rail, and aircraft	Indoor, residential, suburban, field survey
30	Chauhan, et al. 2024	India	Road	Outdoor, urban, field survey
31	Yadav et al. 2025	India	Road	Outdoor, shopkeepers and other workers at traffic intersections, urban, field survey
32	Nadri, et al. 2023	Iran	Rail	Indoor, workplace (subway platform and subway control room)
33	Chung, et al. 2023	South Korea	Rail	Controlled listening environment
34	Weidenfeld, et al. 2024	Germany	Rail	Controlled listening environment, conventional vs replacement brakes
35	Nguyen, et al. 2025	Vietnam	Aircraft	Indoor, residential, urban, field survey
36	Nguyen, et al. 2023	Vietnam	Aircraft	Indoor, residential, urban, field survey
37	Starke, et al. 2023	Germany	Road, rail, and aircraft	Indoor, residential, urban, field survey
38	Dzhambov, et al. 2025	Bulgaria	Road, rail, and aircraft	Indoor, residential, urban, field survey
39	Jovanovic, et al. 2023	Canada	Aircraft	Noise contour modeling methods development
40	Banks, et al. 2025	United States	Aircraft	Indoor, residential, field survey
41	Huang, et al. 2023	China	Aircraft cabin	Controlled listening environment

Ref No.	Author, Year	Country	Noise Source	Research context
42	Boucher, et al. 2024	United States	Helicopter	Controlled listening environment
43	Boucher, et al. 2025	United States	Helicopter	Controlled listening environment
44	Boucher, et al. 2023	United States	Helicopter	Controlled listening environment
45	Pieren, et al. 2024	Switzerland	New aircraft concept	Controlled listening environment
46	Kawai, et al. 2024	Switzerland	Unmanned aircraft systems / drones	Controlled listening environment
47	Lotinga, et al. 2025	United Kingdom	Unmanned aircraft systems / drones	Controlled listening environment
48	Müller, et al. 2025	Germany	Wind turbine	Indoor, residential, suburban, field survey
49	Müller, et al. 2023	Germany	Wind turbine	Indoor, residential, suburban, field survey
50	Zhang, et al. 2025	Japan	Wind Turbine	Outdoor, residential, suburban, field survey
51	Garcia-Guerrero, et al. 2025	Ireland	Wind turbine	Controlled listening environment
52	Ruaud and Dutilleux 2023	Norway	Wind turbine	Outdoor , listeners, laboratory
53	Schmidt et al 2025	Netherlands	Wind turbine	Outdoor, residential, field survey
54	Chen, et al. 2024	China	Floor impact and general	Controlled listening environment
55	Kim, et al. 2023a	South Korea	Floor impact	Indoor, residential, urban, field survey and controlled listening environment
56	Kim, et al. 2023b	South Korea	Floor impact	Indoor, residential, urban, field survey
57	Pinsonnault-Skvarenina, et al. 2025	Canada	Construction	Indoor, residential, urban, field survey
58	Park et al, 2025	South Korea	Road, rail	Indoor, residential, suburban, field survey

Ref No.	Author, Year	Country	Noise Source	Research context
59	Andargie, et al. 2023	Canada	Floor impact	Indoor, residential, urban, field survey
60	Lam, et al. 2023	Singapore	Road, rail, and aircraft	Controlled listening environment
61	Asghari, et al. 2025	Iran	Occupational	Indoor, steel factory, field survey
62	Azzi, et al. 2025	Lebanon	Unspecified	Indoor, school, field survey
63	Bergefurt, et al. 2024	Netherlands	Occupational	Indoor open-plan office, field survey
64	Vreman, et al. 2024	Netherlands	Hospital	Indoor, hospital intermediate care unit, field survey
65	Liu, et al. 2023	China	Ship cabin, noise and vibration	Indoor, crew/passenger cabins, field survey
66	Cai, et al. 2023	Hong Kong, China	General	Indoor and outdoor, residential and occupational, urban, field survey
67	Kuusinen, et al. 2024	Finland	Wideband	Controlled listening environment
68	Song, et al. 2024a	China	General	Indoor and outdoor, residential and occupational, urban, field survey
69	Song, et al. 2025	China	General	Indoor and outdoor, residential and occupational, urban, field survey (mobility based)
70	Huang, et al. 2024	United States	Road, rail, and aircraft	Environmental justice
71	Marquis-Favre, et al. 2023	France	Road, rail, and aircraft	Methods development, estimating noise indices from L_Aeq
72	Kawai, et al. 2025	Switzerland	Urban noise	Outdoor, residential, green spaces, urban, field survey
73	Van Renterghem, et al. 2023	Belgium	Road	Controlled virtual reality environment, effect of greenery on noise annoyance
74	Gjestland, 2024a	International	General	Methods development, effects of survey protocols and analysis techniques
75	Gjestland, 2024b	International	Road, rail, and aircraft	Methods development, first-principles analysis, community tolerance level

Ref No.	Author, Year	Country	Noise Source	Research context
76	Yang, et al. 2024	China	Environmental noise in a park	Methods development, soundscape appropriateness
77	Wilk-Jakubowski et al 2025	Poland	General	Review paper
78	Wang, et al. 2023	China	Road	Methods development, deep learning model to assess annoyance
79	Song, et al. 2024b	China	General	Indoor and outdoor, residential and occupational, urban, field survey (mobility based)
80	Socher, et al. 2025	Germany	General	Controlled listening environment, stability of noise annoyance
81	Forlim, et al. 2024	Germany	Inaudible infrasound	Indoor, residential, urban, randomized-controlled trial
82	Senerth, et al. 2024	International	General	Review paper and meta-analysis

[i] Nature relatedness is a psychological construct measuring an individual's affective, cognitive, and physical connection to the natural world.

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Noise as a Public Health Problem

Health Impacts of Environmental Noise Exposure in the Western Pacific Region: A Regional Evidence Synthesis (2000–2025)

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ABSTRACT

Environmental noise is an emerging public health issue in the Western Pacific Region (WPR), where rapid urbanization and intensive transport activity contribute to widespread exposure to road traffic, railway, aircraft, and recreational noise. This paper presents a regional evidence synthesis of peer-reviewed studies published between 2000 and 2025 on the health effects of environmental and leisure noise in the WPR. Literature searches were conducted using PubMed, Web of Science, and ScienceDirect, focusing on studies related to annoyance, sleep disturbance, cardiovascular disease, mental health, and recreational noise impacts. The reviewed evidence indicates that annoyance and sleep disturbance are the most consistently reported non-auditory effects of environmental noise in the region. Exposure–response relationships differ from European reference data in several WPR settings. Road traffic noise annoyance is generally lower in Vietnam and Hong Kong, whereas railway noise, particularly high-speed rail, tends to produce higher annoyance and sleep disturbance in Japan, China, and the Republic of Korea. Nighttime noise exposure is strongly associated with sleep impairment and may contribute to cardiovascular risk. Mental health outcomes are influenced not only by noise exposure but also by noise sensitivity and perceived environmental conditions. Recreational noise studies reveal widespread unsafe listening behaviors among adolescents and young adults, with increasing risks of hearing damage associated with personal listening devices and entertainment venues. The findings highlight substantial regional variation in community responses to environmental noise and emphasize the need for WPR-specific exposure–response relationships, improved epidemiological evidence, and integrated noise management policies adapted to regional social and cultural contexts.

INTRODUCTION

The Western Pacific Region (WPR) represents an important context for environmental noise research because of its rapid urbanization, high population density, and intensive transport

activity, including road traffic, railways, and aviation systems. In many metropolitan areas, residential districts are located in close proximity to transport infrastructure and commercial activities, resulting in widespread and chronic exposure to environmental noise. In addition, regional differences in housing conditions, urban structure, lifestyle, and cultural attitudes toward noise may influence community responses and health outcomes. Environmental noise has increasingly been recognized as a public health issue associated with a range of adverse effects, including annoyance, sleep disturbance, cardiovascular disease, mental health impacts, and hearing problems related to recreational noise exposure. While the World Health Organization (WHO) Environmental Noise Guidelines for the European Region provide important methodological frameworks and exposure–response relationships for transport noise, evidence from several WPR countries suggests that community responses in the region may differ from those observed in Europe. In particular, previous studies have reported lower annoyance responses to road traffic noise in some Southeast Asian settings, while railway noise, especially high-speed rail, appears to produce stronger annoyance and sleep disturbance in parts of East Asia.

Despite growing research interest, epidemiological evidence on environmental noise and health in the WPR remains unevenly distributed across countries and health outcomes. Most published studies originate from Japan, China, the Republic of Korea, Australia, and Vietnam, whereas little evidence is available from many Pacific island countries and areas. Furthermore, differences in exposure assessment methods, annoyance evaluation scales, and study designs make regional comparison difficult.

This paper presents a regional evidence synthesis of peer-reviewed studies published between 2000 and 2025 on the health impacts of environmental and recreational noise in the WPR. The review focuses on annoyance, sleep disturbance, cardiovascular disease, mental health effects, and recreational noise-related outcomes. The objective is to summarize current evidence, identify regional characteristics in exposure–response relationships, and discuss implications for future research and noise management policies in the Western Pacific Region.

LITERATURE SEARCH

Peer-reviewed studies on environmental noise and health published between 2000 and 2025 were identified through searches of PubMed, Web of Science, and ScienceDirect. The review focused on studies conducted in countries and areas of the Western Pacific Region and included research related to annoyance, sleep disturbance, cardiovascular disease, mental health, and recreational noise impacts. Search terms combined noise-related keywords (e.g., road traffic noise, railway noise, aircraft noise, leisure noise, environmental noise) with health outcomes of interest.

The inclusion criteria were: (1) peer-reviewed articles published in English; (2) studies conducted in countries and areas of the Western Pacific Region; (3) studies addressing environmental or recreational noise exposure; and (4) observational, epidemiological, experimental, or review studies reporting relevant health outcomes. Studies focused exclusively on occupational noise exposure were excluded. Reference lists and several relevant papers from the authors' collections were also examined to identify additional studies.

After screening titles and abstracts, eligible articles were reviewed in detail. In total, 20 studies on annoyance, 11 on sleep disturbance, 5 on cardiovascular disease, 12 on mental health, and 11 on recreational noise were included in this review. Most identified studies originated

from Japan, China, the Republic of Korea, Australia, and Vietnam, while little or no published evidence was found from many Pacific island countries and areas.

Table 1: Summarizes the literature selection process.

Health outcome	Initial search results	Included studies
Annoyance	142	20
Sleep disturbance	235	11
Cardiovascular disease	402	5
Mental health	76	12
Recreational noise	355	11

This review was limited to English-language peer-reviewed publications and did not systematically include grey literature, governmental reports, conference proceedings, or unpublished studies. Therefore, evidence from several countries and local contexts in the Western Pacific Region may remain underrepresented.

RESULTS

Annoyance

Annoyance is recognized by the World Health Organization (WHO) as an adverse health outcome of environmental noise exposure and is widely used in exposure–response assessments. Studies conducted in the Western Pacific Region (WPR) investigated annoyance related to road traffic, railway, aircraft, wind turbine, and construction noise using questionnaire-based socio-acoustic surveys. Most studies applied standardized annoyance questions consistent with ISO/TS 15666 and expressed outcomes as the percentage of highly annoyed persons (%HA). Exposure–response relationships were commonly evaluated using indicators such as L_{den}, and L_{ep},. However, differences in exposure assessment methods, annoyance scales, and cutoff criteria limit direct comparison among studies.

Previous reviews have shown that non-acoustic factors—including age, housing conditions, attitudes toward the noise source, cultural background, and lifestyle—substantially influence annoyance responses (Guski et al., 2017). Similar tendencies were observed in the WPR. Studies in Vietnam (Phan et al., 2010; Nguyen et al., 2016) and Hong Kong (Brown et al., 2015) indicated lower annoyance from road traffic noise than predicted by European exposure–response relationships, despite relatively high exposure levels. In contrast, Japanese studies reported higher annoyance responses at elevated noise levels, possibly reflecting stronger expectations regarding environmental quietness and residential acoustic quality (Figure 1).

Railway noise studies from Japan, China, and the Republic of Korea (Lim et al., 2006; Tetsuya et al., 2017; Zhang & Ma, 2021; Yokoshima et al., 2021) generally showed stronger annoyance responses than those reported in European datasets, particularly for high-speed railway systems. In China and Korea, exposure–response curves for high-speed rail frequently exceeded WHO reference relationships, suggesting increased sensitivity to railway noise in densely populated urban environments (Figure 2). Sleep disturbance and negative attitudes toward railway development were also associated with higher annoyance levels.

Aircraft noise studies in Japan, Korea, and Vietnam (Lim et al., 2007, 2008; Nguyen et al., 2011, 2020; Yokoshima et al., 2021) demonstrated considerable regional variation in

annoyance responses (Figure 3). Japanese and Korean populations generally showed higher annoyance than predicted by international reference curves, whereas Vietnamese exposure–response relationships differed substantially from European data. Background environmental conditions, housing characteristics, and lifestyle factors such as sleep habits were suggested as contributing factors influencing community response.

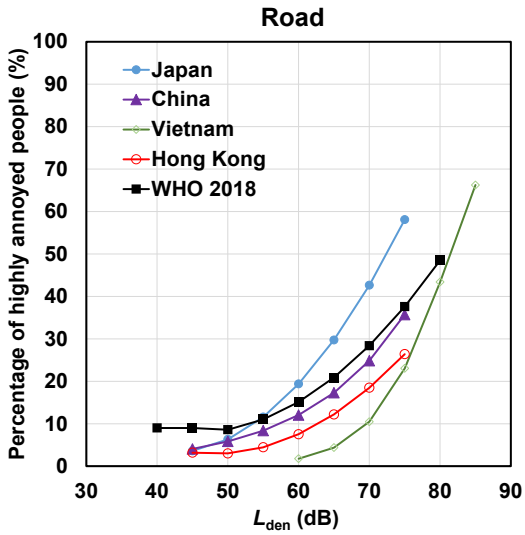

Figure 1: Exposure–response relationships between road traffic noise (L_{den}, dB) and the percentage of highly annoyed persons (%HA) in selected Western Pacific countries

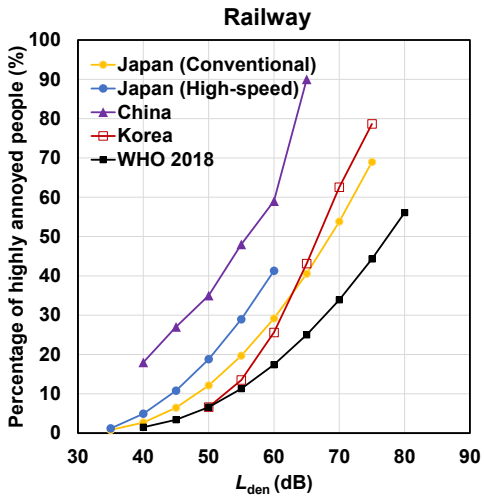

Figure 2: Exposure–response relationships between railway noise (L_{den}, dB) and the percentage of highly annoyed persons (%HA) in selected Western Pacific countries.

Wind turbine noise studies in Japan reported relatively high annoyance associated with low-frequency noise and sleep-related complaints, although direct physiological effects remain unclear (Kuwano et al., 2014). Compared with the exposure–response relationship proposed by Janssen et al. (2011), Japanese respondents appeared more sensitive to wind turbine noise. Construction noise studies in China and Korea also showed strong associations between annoyance and factors such as noise level, construction timing, and interference with daily activities (Liu & Skitmore, 2017). Willingness-to-pay analyses further suggested substantial social demand for construction noise mitigation.

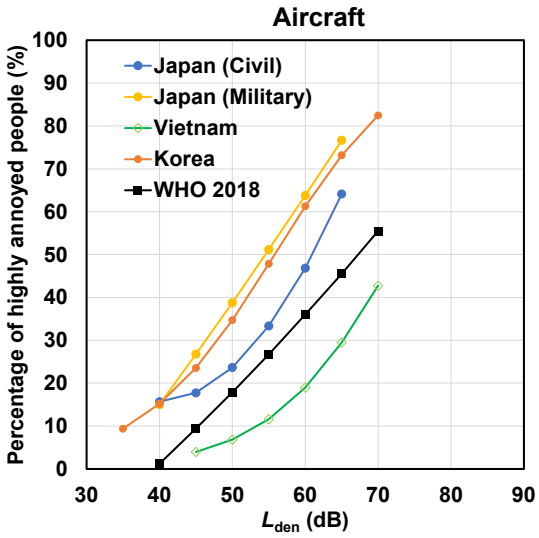

Figure 3: Exposure–response relationships between aircraft noise (L_{den}, dB) and the percentage of highly annoyed persons (%HA) in selected Western Pacific countries.

Wind turbine noise studies in Japan reported relatively high annoyance associated with low-frequency noise and sleep-related complaints, although direct physiological effects remain unclear (Kuwano et al., 2014). Compared with the exposure–response relationship proposed by Janssen et al. (2011), Japanese respondents appeared more sensitive to wind turbine noise. Construction noise studies in China and Korea also showed strong associations between annoyance and factors such as noise level, construction timing, and interference with daily activities (Liu & Skitmore, 2017). Willingness-to-pay analyses further suggested substantial social demand for construction noise mitigation.

Overall, the reviewed studies indicate clear regional differences in exposure–response relationships within the WPR. Compared with European reference relationships, populations in several WPR countries generally exhibited lower annoyance to road traffic noise but higher annoyance to railway and some aircraft noise sources. Logistic regression analyses further demonstrated that annoyance responses were influenced not only by acoustic exposure but also by age, gender, housing type, noise sensitivity, and cultural context (Yokoshima et al., 2021; Zhang & Ma, 2021). These findings support the need for region-specific exposure–response relationships and noise management strategies in the WPR.

Sleep effects

Sleep disturbance is one of the most consistently reported non-auditory effects of environmental noise exposure. Nine peer-reviewed studies conducted between 2000 and 2025 in Japan, China, Hong Kong, the Republic of Korea, and Malaysia examined associations between environmental noise and sleep outcomes using questionnaire surveys and, in some cases, objective sleep measurements.

For road traffic noise, Daruis et al. (2014) did not identify a significant association between proximity to major roads and insomnia in Malaysia. However, studies in Japan, Korea, and Hong Kong (Kawada et al., 2003; Hong et al., 2010; Brown et al., 2015; Morinaga et al., 2025) consistently reported increased percentages of highly sleep disturbed persons (%HSD) with increasing nighttime noise levels (L_{night}). The observed exposure–response relationships were generally comparable to those proposed in the WHO Environmental Noise Guidelines (2018) (Figure 4).

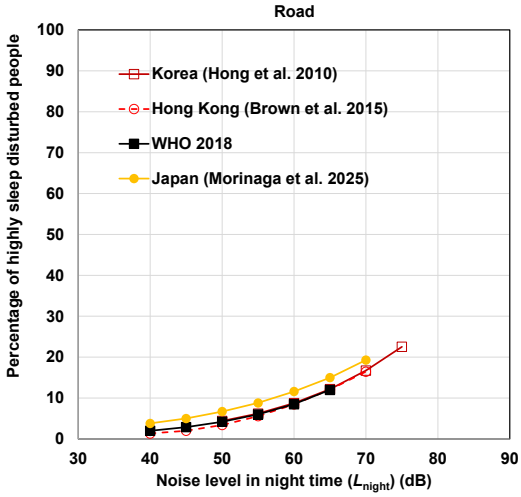

Figure 4: Exposure–response relationships between road traffic noise (L_{night}, dB) and the percentage of highly sleep disturbed persons (%HSD) in selected Western Pacific countries.

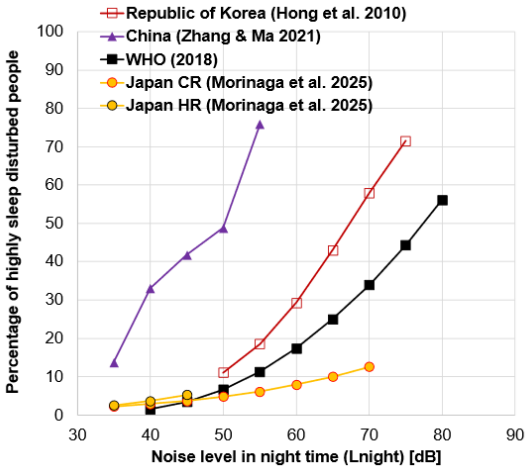

Figure 5*:* Exposure–response relationships between railway noise (L_{night}, dB) and the percentage of highly sleep disturbed persons (%HSD) in selected Western Pacific countries.

Railway noise showed stronger associations with sleep disturbance than road traffic noise. Studies in Korea and China (Hong et al., 2010; Zhang & Ma, 2021) reported exposure–response relationships exceeding WHO reference curves, particularly for high-speed railway exposure. In contrast, Morinaga et al. (2025) reported lower response levels in Japan than WHO estimates (Figure 5). These differences suggest that sleep responses to railway noise may vary substantially depending on local environmental and cultural conditions.

For aircraft noise, sufficient data to establish practical L_{night} -%HSD relationships were not available in the WPR. Nevertheless, WHO guidelines recommend nighttime exposure levels below 40 dB L_{night} for aircraft noise, below 44 dB for railway noise, and below 45 dB for road traffic noise.

Wind turbine noise studies in Japan showed increased odds of insomnia and sleep-related symptoms at nighttime exposure levels exceeding 40 dB L_{night} (Kageyama et al., 2016). Although the prevalence of sleep disturbance was lower than for transport noise, noise sensitivity and attitudes toward wind turbines strongly influenced reported outcomes. Construction noise was also associated with sleep disturbance in urban China, although quantitative exposure–response relationships were not established (Liu & Skitmore, 2017).

Yamagami et al. (2023) further demonstrated associations between higher nighttime indoor noise levels and poorer sleep quality using both actigraphy and self-reported sleep measures among older adults in Japan. Their findings suggest that indoor acoustic environments may significantly influence sleep quality independently of specific outdoor noise sources.

Overall, the reviewed studies consistently indicate that environmental noise contributes to sleep disturbance in the WPR, with railway noise often producing stronger effects than road traffic noise. Psychosocial factors, including depression, stress, major life events, and noise sensitivity, also modified sleep outcomes. The findings generally support WHO exposure–response relationships while highlighting important regional differences requiring further investigation.

Cardiovascular disease

Available epidemiological evidence suggests that environmental noise exposure may contribute to cardiovascular disease (CVD) risk through mechanisms related to stress activation and sleep disturbance. In Japan, Azuma and Uchiyama (2017) reported that elderly residents exposed to construction, neighborhood, and automobile noise—particularly during nighttime—experienced more frequent cardiovascular-related symptoms such as chest pain, irregular pulse, and limb numbness.

Using national health insurance and environmental monitoring data in Korea, Oh et al. (2019) estimated that each 1 dB(A) increase in daytime environmental noise was associated with increases of 0.66% in cardiovascular disease prevalence, 0.17% in hypertension, and 0.38% in heart disease prevalence. Their results suggested that large-scale noise reduction policies could substantially reduce the burden of hypertension and cerebrovascular disease.

Experimental evidence also supports biological effects of nighttime noise exposure. Lechat et al. (2022) demonstrated that moderate nighttime sound exposure induced measurable vascular responses during sleep, with road traffic noise producing stronger effects than wind turbine noise.

Systematic reviews and meta-analyses further indicate significant associations between environmental noise exposure and hypertension risk. Chen et al. (2021) reported a pooled risk ratio of 1.18 for hypertension associated with environmental and occupational noise exposure, with an estimated 13% increase in hypertension risk per 10 dB(A) increase in noise exposure.

However, epidemiological evidence within the WPR remains limited and concentrated in a small number of countries. Most available studies are cross-sectional, and large-scale cohort studies with detailed exposure assessment remain scarce. Current evidence nevertheless supports the hypothesis that environmental noise contributes to cardiovascular risk, particularly through chronic stress responses and sleep disturbance pathways.

Mental health

Recent studies in the WPR indicate that environmental noise exposure may adversely affect mental health and psychological well-being. Although mental health outcomes are not currently classified as critical outcomes in the WHO Environmental Noise Guidelines (2018), evidence increasingly suggests associations between environmental noise and depression, anxiety, stress, insomnia, and reduced quality of life.

Kishikawa et al. (2009) reported significant associations between traffic noise exposure, noise sensitivity, and psychiatric symptoms in Japan, with sleep disturbance identified as an important mediating pathway. Lim et al. (2018) found that both environmental noise exposure and noise sensitivity were associated with internalizing and externalizing behavioral problems among children and adolescents in Korea, particularly in lower-income groups.

Prospective cohort evidence from Hong Kong showed that residential road traffic noise exposure was associated with increased depression risk and poorer mental well-being, especially among younger populations and students (Shi et al., 2023). Similarly, Park et al. (2017) demonstrated that noise sensitivity was more strongly associated with depression, anxiety, and insomnia than measured environmental noise levels themselves.

Several studies highlighted the importance of subjective perception and cumulative environmental exposure. Ma et al. (2020) showed that higher perceived noise exposure was associated with increased stress, fatigue, headaches, anxiety, and sleep disturbance. Using portable monitoring devices and GPS-based exposure assessment, the study further suggested that cumulative 24-hour exposure may better predict mental health outcomes than static residential measurements.

Studies comparing China, Japan, and Korea also demonstrated that perceived environmental pollution was associated with poorer mental health and reduced quality of life (Kamimura et al., 2017). In addition, simultaneous exposure to air pollution and noise was shown to increase psychological stress during daily activities such as commuting (Tao et al., 2021).

Overall, mental health effects appeared to be strongly influenced by noise sensitivity, socioeconomic status, subjective perception, and combined environmental stressors. Although causal relationships remain difficult to establish, the reviewed evidence suggests that environmental noise may contribute to adverse psychological outcomes, particularly in urban environments with multiple environmental stressors.

Recreational noise impact

Recreational noise exposure has emerged as an important public health concern in the WPR, particularly among adolescents and young adults. Major sources include personal listening devices (PLDs), portable music players, concerts, sports events, and nightclubs. The most consistently documented outcomes are noise-induced hearing loss (NIHL) and tinnitus. Systematic reviews indicate that recreational noise exposure is associated with permanent hearing loss and tinnitus, although evidence for cardiovascular, cognitive, and annoyance-related outcomes remains limited (Sliwinska-Kowalska & Zaborowski, 2017). Dillard et al. (2022) estimated that between 670 million and 1.35 billion young people worldwide may be at risk from unsafe listening practices.

Studies in Australia reported that approximately 14% of young adults were exposed to recreational noise levels exceeding occupational safety standards, particularly in nightclubs, and exposed individuals reported increased tinnitus and perceived hearing difficulties (Gilliver et al., 2012; Beach et al., 2013). In Singapore, up to one-sixth of youths reportedly listened to music above recommended safe levels, and otoacoustic emission measurements identified early cochlear changes among high-risk listeners (Lee et al., 2014). Korean studies further reported hearing impairment among approximately 17% of adolescents, associated with both

PLD use and exposure to noisy recreational environments such as sports stadiums and gaming centers (Rhee et al., 2019; Kim et al., 2021).

Several studies also indicated that hearing loss and tinnitus may negatively affect academic performance and daily communication among adolescents and young adults. Despite relatively high awareness of hearing risks, protective behaviors such as reducing listening volume or using hearing protection remained limited. The reviewed evidence indicates that recreational noise exposure is an increasing health concern among young populations in the WPR. Hearing loss and tinnitus are the most consistently observed outcomes, highlighting the need for preventive education, safer listening practices, and further epidemiological research in the region.

CONCLUSION

Environmental noise is an important public health issue in the Western Pacific Region (WPR), where rapid urbanization and dense transport systems expose large populations to road traffic, railway, aircraft, construction, and recreational noise. Available studies indicate that residents in several WPR countries are exposed to approximately 40–85 dB from road traffic noise, 35–80 dB from railway noise, and 35–70 dB from aircraft noise. Beyond auditory effects, evidence from the region consistently demonstrates associations between environmental noise exposure and annoyance, sleep disturbance, cardiovascular effects, mental health outcomes, and recreational noise-related hearing risks.

The reviewed studies revealed substantial regional variation in exposure–response relationships. Road traffic noise annoyance in Vietnam and Hong Kong was generally lower than European reference relationships, whereas railway noise—particularly high-speed rail—and some aircraft noise produced stronger annoyance responses in Japan, China, and the Republic of Korea. Sleep disturbance was consistently associated with increasing nighttime noise exposure, with railway noise often showing stronger effects than road traffic noise. Evidence regarding cardiovascular disease and mental health remains more limited but suggests that stress, sleep disruption, and noise sensitivity may play important roles in mediating health impacts. Recreational noise exposure from personal listening devices, concerts, nightclubs, and sports venues was identified as an emerging concern among adolescents and young adults, particularly in Australia, Singapore, and the Republic of Korea.

This review identified 21 studies on annoyance, 8 on sleep disturbance, 5 on cardiovascular disease, 12 on mental health, and 11 on recreational noise published between 2000 and 2025. However, evidence remains concentrated in a limited number of countries, with little or no published data from many Pacific island countries and areas. In addition, methodological differences in exposure assessment, annoyance scales, sleep evaluation, and definitions of noise sensitivity limit direct comparison among studies and complicate the development of harmonized exposure–response relationships for the region.

Future research in the WPR should prioritize large-scale socio-acoustic and epidemiological studies using standardized exposure assessment methods, including strategic noise mapping. Standardization of sleep disturbance assessment and noise sensitivity evaluation is also needed to improve comparability across countries and studies. Further cohort studies, particularly on sleep and cardiovascular outcomes, are essential to strengthen the evidence

base for region-specific environmental noise policies and public health interventions in the Western Pacific Region.

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Exposure-response relationship of civil shooting range noise

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ABSTRACT

Target values for shooting range noise should be based on population studies. However, such studies have not been conducted in Finland. The metric of Finnish target value for shooting range noise is L_{AImax}. It has been criticized since L_{AImax} value only depends on the properties of the loudest impulse, not on the total daily noise exposure. L_{den} is increasingly applied as a metric of environmental noise because it is an energy-based noise exposure quantity. The aim of this cross-sectional study was to determine the exposure-response relationship (ERR) of shooting range noise, i.e., how high annoyance depends on L_{den}. The sound levels of three civil shooting ranges in Finland were simulated for the yards of all households located within 2 km radius of the ranges. Altogether 1816 questionnaires were mailed and 223 responses were received. Percentage of respondents reporting high annoyance (%HA) was clearly dependent on the sound level. EERs were quite similar between the three shooting ranges. Our results suggest that sound levels above 25 dB L_{den} should be avoided if the goal is %HA<10%. A significant association was found between HA and age group, and prior awareness of the range. Our study gives strong support of using L_{den} as the metric of future Finnish target values because it takes the total number of annual shoots, i.e., total energy, into account. The application of L_{AImax} is also problematic since it cannot be measured with many new commercial sound level meters. Furthermore, it cannot be modelled with energy-based software.

INTRODUCTION

There is pressure to renew the Finnish Government Decision 53/1997 on Environmental Noise from Civilian Shooting Ranges [1]. The decision uses the measurement quantity L_{AImax}, (A-weighted maximum impulse weighted sound pressure level) which is not available in many new sound level meters. The use of this quantity is not based on scientific exposure–response relationships. Furthermore, it cannot be determined using sound level modelling software that examines total acoustic energy, because its value also depends on the waveform of the signal

(the onset rate of the impulse decreases with increasing distance because of several reflection paths).

The Finnish Government Decree on Noise Levels from Heavy Weapons and Explosions (903/2017) [2] (which applies to Defence Forces shooting ranges and weapons testing areas) uses the annual day-evening-night sound level L_{Rden} as the land-use planning quantity. It considers the total energy of all events. It applies an impulsiveness penalty (i.e., adjustment or sanction) of 15 dB. In short-term measurements, the maximum sound exposure level of a single shooting event, L_{CE}, is used. Both quantities can be determined from total energy using noise modelling. Similar quantities could also be applicable to civilian shooting ranges, but the setting of the target values requires field research among residents.

The guidelines for shooting range noise should be based on justified quantities and numerical guideline values assigned to them. Internationally, common practice is to base guidelines on exposure–response relationships derived from population studies, which describe how subjective noise annoyance depends on sound level. In Finland, such studies have been conducted for road traffic and wind turbine noise [3,4], but not for shooting range noise.

The aim of our study was to determine how the annoyance caused by shooting range noise is related to the annual day–evening–night sound level (L_{den}). In addition, our aim was to investigate how certain non-acoustic factors are associated with noise annoyance.

METHODS

The study was conducted as a cross-sectional study. The independent variables were the day–evening–night sound level L_{den}, and the shooting range area (municipality). The dependent variable was noise annoyance outdoors, which was asked using an 11-point scale (0 = Not at all … 10 = Very much) by item “How much does the shooting range noise disturb, bother, or annoy you when you spend time outside in the garden, balcony or terrace of your home? Think about the situation in the past year.”. The questionnaire involved non-acoustic variables (*age group*, *gender*, *housing type*, *responders’ hunting or range shooting leisure activity*, *responder’s family members hunting or range shooting leisure activity*, *responders’ involvement with the shooting range*, and *being aware of the shooting range before moving to the area*). Their association with high annoyance was studied using Chi-squared test or with Fishers exact test.

Noise exposure in residents’ yards was determined using CadnaA. The primary modelled parameter was the sound level $L_{den,i}$ of each weapon type *i* used in the range. It was determined based on the annual number of shots fired for that weapon type and its sound energy level $L_{J,I}$, during the whole year. The total noise exposure $L_{den,tot}$, calculated for respondents was the superposition of the $L_{den,i}$ values of all weapon types at the shooting range. Annual numbers of shots were based on estimates provided by range masters for the years 2022–2024. No impulsivity penalty was applied to L_{den} in our study, since the suitable penalty value is level dependent [5]. One of the driving purposes of our study was to propose the suitable penalty for shooting range noise in the future legislations so that we did not apply any value at this point.

We aimed to obtain as many respondents as possible with as small number of shooting ranges as possible. We selected three ranges located close to relatively densely populated areas. The ranges were located in the municipalities of Harjavalta, Puumala and Leppävesi. Households included in the survey were those located within 2 km in front of and to the sides of the shooting range, and within 1 km behind it. A total of 1816 households were identified

across the three areas. Questionnaires were sent to households by post, and responses could be submitted either on paper or electronically. A total of 223 responses were received (response rate 12.2%).

The exposure–response relationship was determined by dividing residents' noise exposures into L_{den} categories with a width of 5 dB. Annoyance was classified as high (High Annoyance, HA) if the respondent's rating of shooting range noise annoyance was 8, 9, or 10. For each category, the proportion of respondents (%HA) experiencing high annoyance was calculated.

RESULTS AND DISCUSSION

Annual noise exposure values among respondents ranged from −1.1 to 39.1 dB L_{den}. These values do not include any impulsivity penalty corrections. The range was sufficiently wide for determining an exposure–response relationship. The values appear to be small. It must be noted that the shooting range is silent most of the time. Shooting range activity is concentrated on daytime hours (10–19) within May–September, therefore the annual L_{den} values are much smaller than the L_{Aeq1h} values during shooting range activity.

The exposure–response relationship describing shooting range sound levels and annoyance is shown in Figure 1**.** High annoyance outdoors clearly depended on sound level. No high outdoor annoyance (%HA = 0) was observed when L_{den} < 15 dB. Above this level, high annoyance increased as L_{den} increased. In many guidelines, the level %HA=10 is considered a threshold value that should not be exceeded. High annoyance exceeded 10% when L_{den} > 25 dB. When compared to other noise sources, high annoyance reaches 20% level in much lower sound levels than for road traffic noise [3] or wind-turbine noise [4] (see Figure 1.).

The exposure–response relationship for shooting range noise did not depend on the shooting range area (municipality). For example, the exposure–response relationship for wind turbine noise has been found to depend strongly on the municipality, because attitudes towards environmental issues or the management of environmental matters vary between municipalities. Range-specific exposure–response relationships cannot be published because, in too many sound level categories, there were fewer than 10 respondents (risk of identification).

Age was divided into three groups (18**–**40; 41**–**60; 60+). A chi-square test of independence showed a significant association between *age group* and HA (p=0.007), with standardized residuals indicating that HA cases were significantly underrepresented in the 18–40 age group and overrepresented in the 60+ age group, while no significant deviation was observed in the 41–60 group. Additionally, a significant association was found between HA and *awareness of the range before moving to the area* (p=0.042), with HA cases overrepresented among those who were not aware of it and underrepresented among those who were aware.

We found no associations with HA with other variables (*gender*, *housing type*, *responders' hunting or range shooting leisure activity*, *responders' family members' hunting or range shooting leisure activity,* nor *responders' involvement with the shooting range*).

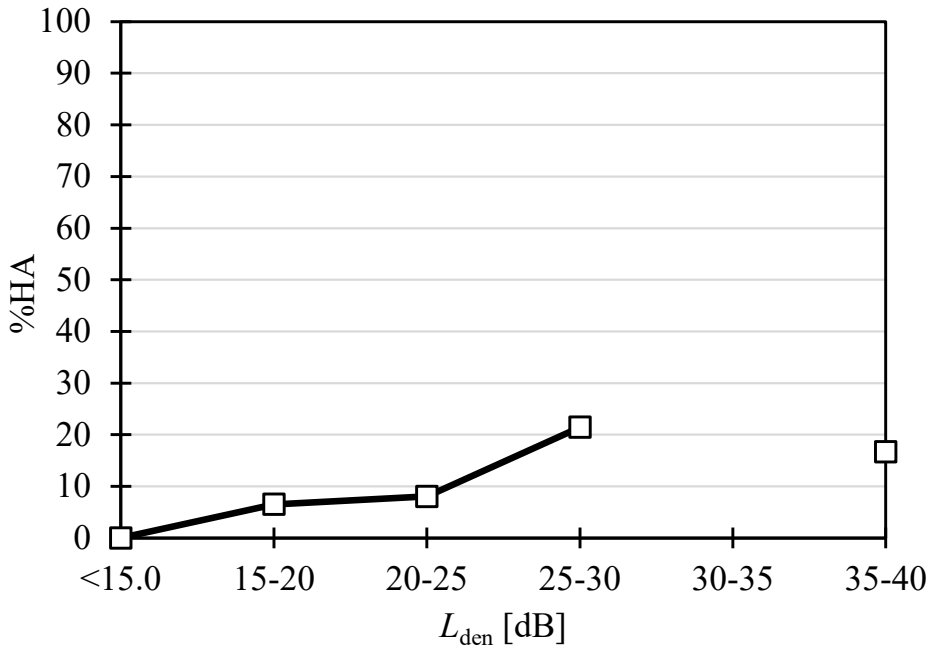

Figure 1: The proportion of respondents reporting high noise annoyance outdoors, %HA, because of shooting range noise as a function of annual day-evening-night level, L_{den}.

CONCLUSION

The perceived annoyance from shooting range noise increased as the day–evening–night sound level L_{den} of the shooting range increased. Our study suggests that L_{den} levels above 25 dB should be avoided if the aim is to keep the proportion of highly annoyed below 10%. Additionally, our results indicate that older responders, and those who were not aware of the shooting range before moving to the area were more likely to report higher levels of annoyance.

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Spectrum affects noise annoyance – Adjustment of sound level based on psychoacoustic evidence

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ABSTRACT

Many noise measurement guidelines involve a penalty procedure where a constant number, *k* [dB], that is added to the measured sound level, L_{Aeq} [dB] if the sound is tonal or impulsive. The adjusted value, $L_{Aeq}+k$, should then describe noise annoyance better than L_{Aeq} alone. However, most sounds in our environment lack temporal variations and tonal features, thus being ordinary broadband steady-state (BBSS) sounds. Our purpose is to summarize psychoacoustic research, which developed a simple model to calculate the annoyance penalty of a BBSS sound, when spectrum is measured using 1/3-octave band analysis. Kuusinen et al. (2023) conducted a psychoacoustic experiment which investigated the annoyance of 23 spectrally different BBSS sounds at levels 32, 40, and 48 dB L_{Aeq}. They reported annoyance penalty values to be within 0 and +12 dB. The finding proved that penalty is justified also for BBSS sounds. Interestingly, the penalty obtained for a specific spectrum did not depend on L_{Aeq}. In the follow-up study, Kuusinen & Hongisto (2026) developed a regression model, which predicted the annoyance penalty obtained in the experiment with high reliability (R^2=0.79). The input variable of the model spectral centroid, which is calculated from the 1/3-octave band spectrum of BBSS sound. The model may have broad applications in the assessment of noise annoyance of various BBSS sound scenarios both outdoors and indoors.

INTRODUCTION

Many noise measurement guidelines involve sound level adjustment (also known as penalty, sanction and surplus), if the noise carries specific, and objectively measurable features, such as impulsivity or tonality. In most guidelines, the penalty is constant, *k* [dB], that is added to the measured sound level, L_{Aeq} [dB]. The adjusted value, $L_{Aeq}+k$, should then describe noise annoyance better than L_{Aeq} alone.

Noise annoyance is usually measured using 11-step numerical scale where 0 denotes “Not at all annoyed” and 10 denotes “Extremely annoyed”. Many psychoacoustic experiments have proven that noise annoyance penalty due to sounds carrying abovementioned specific properties cannot be explained using constant penalty models. Instead, the annoyance penalty varies between 0–12 dB for tonal sounds [1, 2] 0–8 dB for normal impulsive sounds [3, 4], and even 20 dB for impulsive shooting sounds [5]. The annoyance penalty strongly

depends on the physical measurable properties of the specific feature. For tonal sounds, such properties are tonal audibility and tonal frequency [1, 2]. For impulsive sounds such properties are onset rate and level difference or variability of sound level [3, 4].

In practice, most sounds in our environment, both indoors and outdoors, are more or less **broadband steady-state** (**BBSS**) sounds, which lack temporal variations and tonal features. A recent psychoacoustic experiment [6] investigated spectrally different BBSSs and found that BBSSs deserve annoyance penalty if the spectrum fulfils certain criteria. The annoyance penalty was even 12 dB for sounds which have strong high frequency content [6]. Based on that work, a follow-up study provided a prediction model [7], which showed how the annoyance penalty could be calculated from the sound pressure levels (SPL) measured using one-third octave band analysis.

Our purpose is to summarize psychoacoustic research, which developed a simple model to calculate the penalty of a BBSS sound, when spectrum is measured using 1/3-octave band analysis within 100–10 000 Hz.

PSYCHOACOUSTIC EXPERIMENT

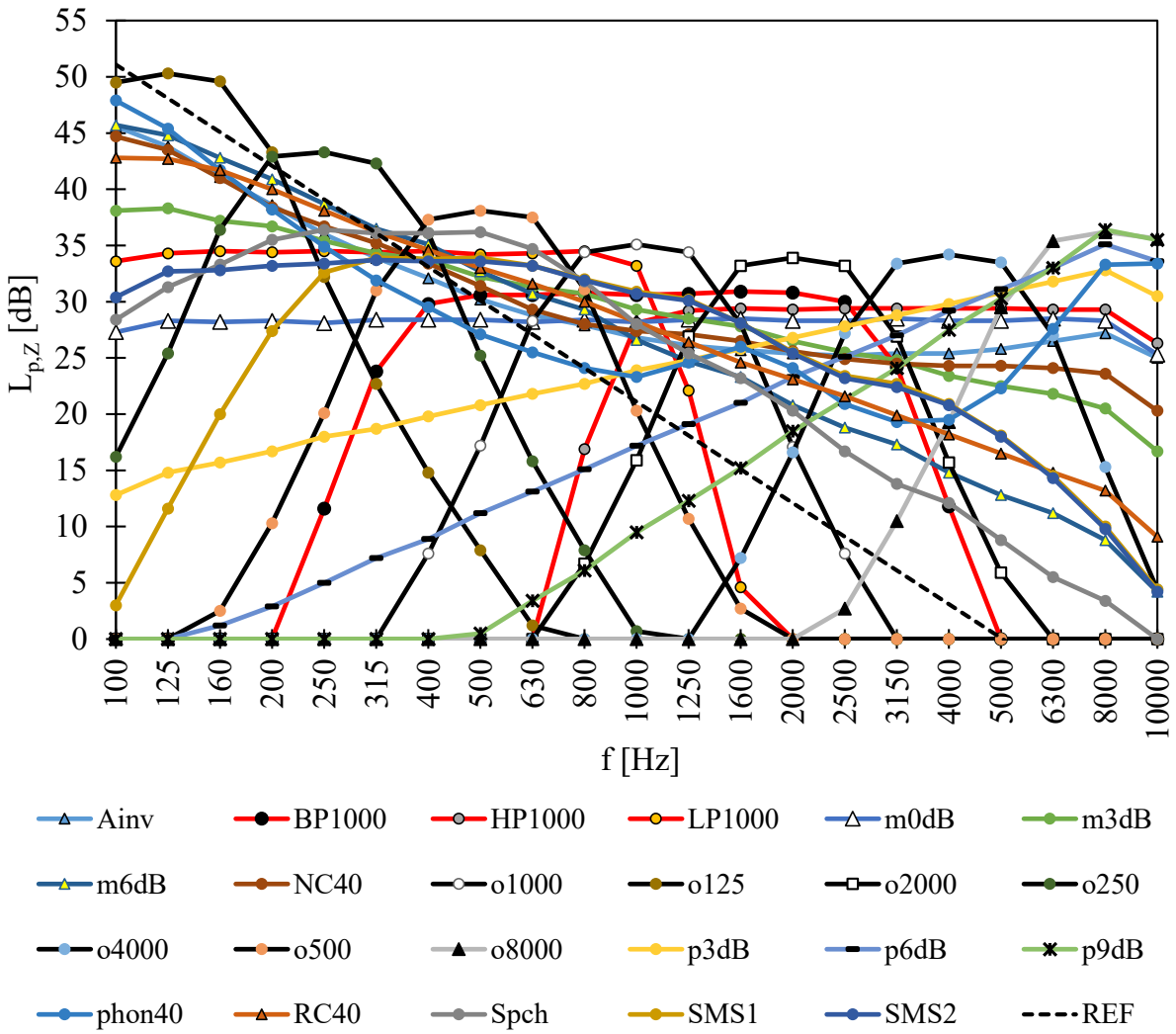
This section summarizes the psychoacoustic experiment [6], which was used in the development of the penalty model.

The psychoacoustic experiment involved 40 participants. Each participant rated the annoyance of 78 stimuli which all were BBSS sounds. The sounds were played via headphones and the listening time was 10 seconds before the rating was possible. The rating was made using abovementioned 11-step numerical response scale. The number of actual research stimulus was 69. They involved 23 different spectral shapes, which were presented at three L_{Aeq} levels (32, 40, 48 dB). In addition, the stimuli involved 9 reference sounds played at 28–60 dB L_{Aeq} in 4-dB steps. Reference sounds had a constant spectrum shape. The spectrum of reference sound pleasant as possible so that all other sounds should be more annoying. The chosen spectrum shape was Brown noise (-9 dB per octave increment) as a previous study found it to be very pleasant [8]. The annoyance of reference sounds depended linearly on LAeq. This line was used to determine the penalty for the 69 research stimuli.

The spectrum shapes and annoyance penalties of the experiment are summarized in Figure 1. Penalty of a specific BBSS spectrum did not strongly depend on L_{Aeq} within 32–48 dB. Therefore, it was justified to develop a calculation model, which could be used to predict the annoyance penalty of any kind of spectrum.

PREDICTION MODEL

The development of the prediction model is explained in detail in Ref. [7]. The work started with the inspection of all previously published models which have been used for the rating of BBSS sounds. First, we studied level-dependent descriptors: Unweighted sound level ($L_{Z,eq}$), A-weighted sound level (L_{Aeq}), Speech Interference Level SIL, Noise Criterion (NC), Preferred Noise Criterion (PNC), Noise Rating (NR), Balanced Noise Criterion (BNC), Room Criterion (RC), Room Noise Criterion (RNC), Loudness level (LL), and Loudness level with Sharpness. Thereafter, we studied spectral shape descriptors: spectral centroid (SC), spectral spread (SS), Sharpness (SH), level difference of low and high frequency bands (LAlohi), Nratio, Nlow, and Quality Assessment Index (QAI).



Sound	k
Ainv	6.6
BP1000	7.1
HP1000	9.4
LP1000	2.3
m0dB	5.9
m3dB	5.3
m6dB	2.8
NC40	6.2
o1000	4.4
o125	0.2
o2000	7.3
o250	-0.7

Sound	k
o250	-0.7
o4000	7.1
o500	3.9
o8000	10.4
p3dB	8.1
p6dB	8.8
p9dB	9.0
phon40	6.8
RC40	3.2
SMS1	3.4
SMS2	2.9
Spch	2.0

Figure 1: The spectra of the 24 BBSS sounds of the psychoacoustic experiment [6]. All spectra are presented at 40 dB L_{Aeq}. REF represents the shape of reference sounds. All the other spectra represent the experimental BBSS stimuli. Table shows the mean subjective penalty obtained for each sound at three levels: 32, 40, and 48 dB L_{Aeq}.

The functioning of these descriptors was investigated using correlation analysis. Since Ref. [6] found that the penalty was independent on L_{Aeq} within 32–48 dB, our main interest is towards spectral shape descriptors.

Sharpness and Spectral centroid were the best objective descriptors for predicting the annoyance penalty. However, the recommended descriptor for practical noise measurements is SC because SC can also be calculated from one-third octave spectrum of noise by Eq. (1):

$$SC = \frac{\sum_{n=1}^{N} f_n \cdot L_n}{\sum_{n=1}^{N} L_n}$$

where f_n [Hz] is the middle frequency of one-third octave band n, and L_n [dB] is the unweighted SPL at the one-third octave band n. In our study, N=21, since the stimuli was limited to 100–10 000 Hz. It should be noted L_n is set to 0 dB that at such bands, where the SPL is either below the hearing threshold level, HTL, or below the threshold of irrelevance, T. It was defined to be T=15 dB in our study.

Annoyance penalty is calculated by Eq. (2):

$$k = 6.9 * log_{10}(SC) - 16.3$$

The prediction accuracy of the model in Equations (1–2) was very good (R^2=0.79). The association between SC and annoyance penalty is illustrated in Figure 2.

An example of the calculation procedure is shown in Figure 3 for one of the BBSS sounds of Figure 1. The predicted penalty of 8.3 dB is very close to the penalty of 8.8 dB reported in Figure 1.

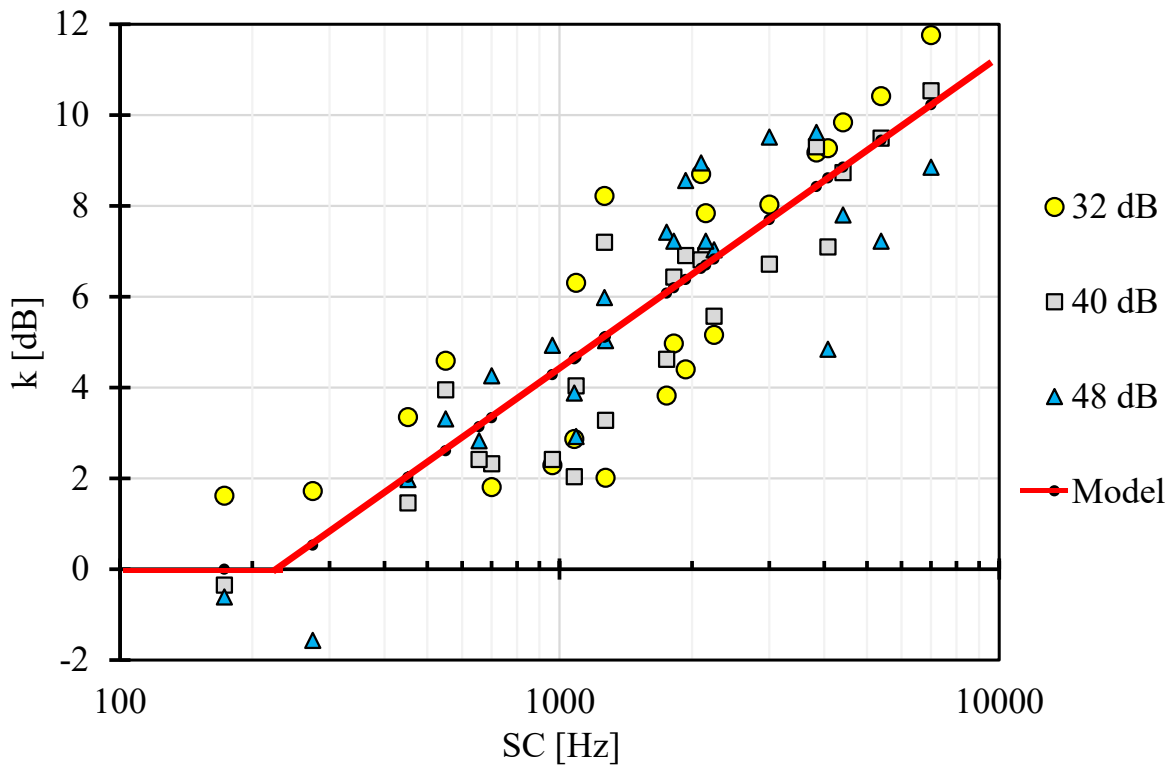


Figure 2: The association between spectral centroid measured for the stimuli, SC, and penalty, k. Symbols represent the subjective penalties obtained for the 69 stimuli of Kuusinen et al. [6] and line represents the penalty given by the prediction model of Equations (1–2).

DISCUSSION

The experimental work and the outcoming prediction model are unique because there are no previous studies which have investigated the annoyance penalty of BBSS sounds in similar depth.

Most noise measurements apply one-third octave band frequency analysis, our model can be easily applied in, e.g., the assessment of building service and environmental sounds indoors or outdoors, development of product sounds, and assessment of soundscapes.

In Ref. [7], the threshold of irrelevance was set to T=15 dB. This selection was based on subjective assessment of BBSSs. Ignoring levels below the threshold yielded good fit between subjective data and prediction model. However, the threshold may require more optimization.

The experiment of Kuusinen et al. [6] was limited to BBSS sounds presented within 100–10 000 Hz. It is still possible that the model may be applicable to a broader frequency range. However, the model should not be applied to tonal sounds.

The experimental work of Kuusinen et al. [6] was limited to sound level range 32–48 dB L_{Aeq}. Because the annoyance penalty did not depend on sound level within that range, it is probably safe to apply the model within 25–55 dB. However, uncertainties may appear beyond that range.

	p6dB	HTL
	3.9	26.5
125	7.1	22.1
	9.2	17.9
	10.9	14.4
250	13.0	11.4
	15.2	8.4
	16.9	5.8
500	19.2	3.8
	21.1	2.1
	23.1	1.0
1000	25.2	0.8
	27.1	1.9
	29.0	0.5
2000	31.3	-1.5
	33.1	-3.1
	35.0	-4.0
4000	37.2	-3.8
	39.1	-1.8
	41.0	2.5
8000	43.1	6.8
	41.6	9.8

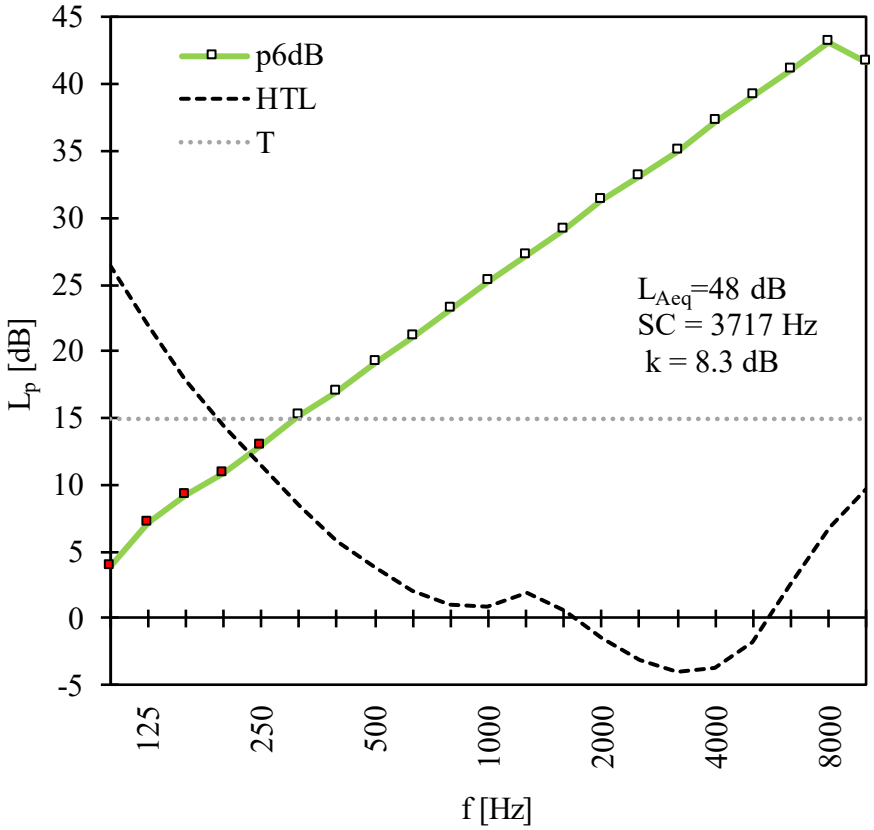


Figure 3: Example of the calculation process of spectral centroid for sound p6dB at(L_{Aeq}=48 dB.

Acknowledgements

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Annoyance penalty of impulsive noise – Adjustment of sound level based on psychoacoustic evidence

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ABSTRACT

Many noise guidelines require that penalty k [dB] shall be added to the measured sound level, L_{Aeq} [dB], if noise is impulsive. The adjusted value, $L_{Aeq}+k$, should then describe noise annoyance better than L_{Aeq} alone. ISO/PAS 1996-3 (Model 1) provides a floating prediction model where the penalty k depends on measurable parameters of the impulse: onset rate (R_{on}) and level difference (D_L). However, Model 1 overestimates the perceived annoyance for many types of impulsive sounds. Our purpose was to test alternative models and determine their prediction accuracy using abovementioned experimental psychoacoustic data. Model 2 was a modification of Model 1. Model 3 was based on level difference $L_{A,I}$ - $L_{A,S}$. Model 4 was based on alternative level difference, $L_{A,F,max}$ - $L_{A,min}$. Model 5 was based on sound level variability, $L_{A,1}$–$L_{A,99}$. All Models 2–5 predicted both subjective annoyance, and annoyance penalty, with higher precision than Model 1. Model 5 is recommended for practical measurements because of its simplicity. The results are applicable for the assessment of impulsive sounds within 45–65 dB L_{Aeq}.

INTRODUCTION

Many kinds of sources involve impulsive sound, e.g., shooting ranges, logistic centres, playing fields, industrial plants, and construction sites. Many guidelines involve a sound level adjustment (a.k.a. penalty or sanction), if the measured noise has impulsive character. In most of them, the penalty is a constant value, k [dB], that is added to the measured sound level, L_{Aeq} [dB]. The outcoming adjusted value, $L_{Aeq}+k$, should then describe noise annoyance better than L_{Aeq} alone. ISO/PAS 1996-3 (Model 1) provides a floating prediction model where the penalty k depends on measurable parameters of the impulse: onset rate (R_{on}) and level difference (D_L). These variables are depicted in Figure 1.

However, there is strong psychoacoustic experimental evidence [1] that Model 1 overestimates the perceived annoyance for many types of impulsive sounds.

The purpose was to test alternative prediction models and determine their prediction accuracy using abovementioned experimental psychoacoustic data. The full version of this study is given in Ref. [2]

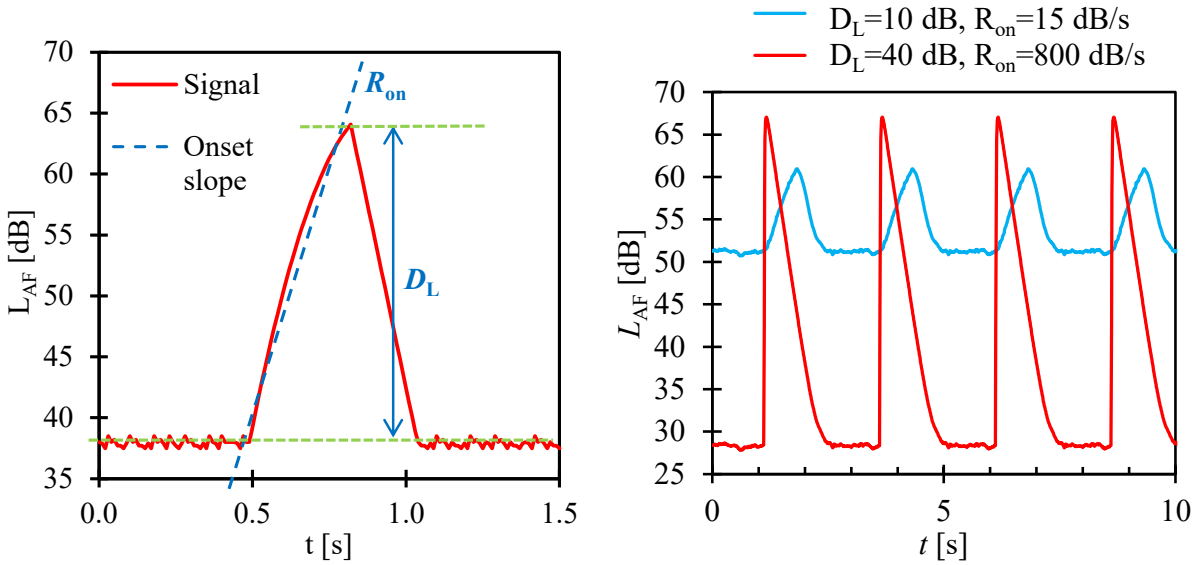

Figure 1. Left) Fast-time weighted SPL, L_{AF}, of an impulse as a function of time, *t*, for a single impulse. The sampling time is 10 ms. Right) Comparison of the time profiles of two different stimuli of Ref. [1]. NOTE: the A-weighted SPL was 55 dB L_{Aeq} for all stimuli.

MATERIALS AND METHODS

This raw data of this work is based on the psychoacoustic experiment of Ref. [1]. They studied how the noise annoyance of impulsive sounds at level 55 dB L_{Aeq} depended on different combinations of R_{on} and D_L (Table 1). The experiment had 32 participants. The number of stimuli was 41 sounds. All of them had the same spectrum shape. Altogether 33 of them were impulsive sounds. The impulses were created from pseudorandom noise by varying the time profile of noise. The impulses were presented using constant period of 2.5 seconds. In addition, 8 steady-state reference sounds were presented within 49–70 dB L_{Aeq} in 3-dB steps. The annoyance vs. L_{Aeq} of the reference sounds formed a straight reference line and this line was used to determine the annoyance penalty of each impulsive sound. The penalty values of the 33 impulsive sounds are shown in Table 1.

Table 1: The dependence of annoyance penalty on level difference and onset rate of the impulse according to the psychoacoustic experiment of Ref. [1].

D_L [dB]	R_{on} [dB/s]									
	5	10	15	20	50	100	200	400	600	800
5	-2.4	-1.5	-1.5	-1.9	-0.7					
10		-1.4	-1.1	1.8	1.2	-0.1				
15			0.9	0.8	2.5	4.4				
20				2.8	3.3	5.3	3.0			
25					3.2	5.4	6.3	6.5		
30					4.9	5.6	7.7	7.7	6.6	
40					6.5	7.4	6.6	8.1	7.9	8.1

Model 1 corresponds to ISO/PAS 1996-3 [3]. The method was adopted from the Nordtest method [4]. Model 1 is based on the microstructure analysis of every impulse using the variables R_{on} and D_L (Figure 1). First, the prominence P is calculated for each impulse by

$$P = 3 \cdot \log_{10}\left(R_{\text{on}}\right) + 2 \cdot \log_{10}\left(D_{\text{L}}\right)$$

P shall be limited to 15 dB. Thereafter, the penalty is calculated by

$$k = \begin{cases} 1.8 \cdot \left(P - 5\right), P > 5 \\ 0, \qquad\qquad P \le 5 \end{cases}$$

Model 2 uses the same input variables as Model 1 so that no more measurements need to be made. However, the functional form of penalty is different. The form was based by fitting the psychoacoustic data of Table 1. It is calculated by

$$k = 11 \cdot \log_{10}\left(\frac{D_L}{7}\right) - \frac{100 \cdot D_L - D_L^{\,2}}{25 \cdot R_{on}}$$

The penalty shall be limited to 12.7 dB.

Model 3 is based on European directive [5]. The impulsiveness is measured using

$$I_3 = L_{\text{A,I}} - L_{\text{A,S}}$$

where $L_{\text{A,I}}$ [dB] is the A-weighted sound pressure level (SPL) using Impulse (I) time weighting of 35 ms, and $L_{\text{A,S}}$ [dB] is the A-weighted SPL using Slow time weighting (1000 ms). Sampling time resolution shall be set to 10 ms. Sound is considered impulsive, if $I_3 \geq 4$ dB.

Model 3 was developed using simple linear regression ($k = aI_3 + b$) between the explaining objective quantity I_3 and the observed penalty of Table 1. The criterion for non-impulsive sound (I_3<4 dB) was considered by forcing predicted k to zero in such situations. The penalty obtained the form

$$k = 0.744\left(L_{\text{A,I}} - L_{\text{A,S}}\right) - 2.039$$

Model 4 is like Model 3 but $L_{\text{A,I}}$ was replaced by $L_{\text{AF,max}}$. Model 4 is justified because $L_{\text{A,I}}$ is no longer available in many sound level meters. The impulsiveness is measured using

$$I_4 = L_{\text{A,F,max}} - L_{\text{A,min}}$$

where $L_{\text{A,F,max}}$ [dB] is the maximum A-weighted SPL using Fast time weighting and sampling rate of 250 ms, and $L_{\text{A,min}}$ [dB] is the minimum SPL that appears between the impulses (background noise).

Model 4 was developed using simple linear regression ($k = aI_4 + b$) between the explaining objective quantity I_4 and the observed penalty of Table 1. The penalty is calculated by

$$k = 0.240\left(L_{\text{A,F,max}} - L_{\text{A,min}}\right) - 1.280$$

Model 5 is based on statistical sound level quantities which are easily available in most sound level meters. Impulsiveness is measured using

$$I_5 = L_{\text{A,1\%}} - L_{\text{A,99\%}},$$

where $L_{\text{A,1\%}}$ [dB] and $L_{\text{A,99\%}}$ [dB] are the SPLs of 1% and 99% percentiles. Analysis is made using Fast time weighting and 10 ms sampling rate.

Model 5 was developed using simple linear regression ($k = aI_5 + b$) between the explaining objective quantity I_5 and the observed penalty of Table 1. The penalty is calculated by

$$k = 0.241\left(L_{\text{A,1\%}} - L_{\text{A,99\%}}\right) - 1.365$$

Statistical analyses

Prediction error *E* [dB] for every impulsive sound i and model M was defined as

$$E_{M,i} = k_{\mathrm{M,i}} - k_{\mathrm{O,i}}$$

where $k_{\mathrm{M,i}}$ [dB] is the predicted penalty of the sound i based on Model M, and $k_{\mathrm{O,i}}$ [dB] is the observed penalty for the same sound I (Table 1).

RESULTS

The precisions of the Models 1–5 are shown in Table 2. All associations were statistically significant ($p<10^{-11}$, 2-sided). The association between observed and predicted penalty for Model 5 is visually demonstrated in Figure 2.

All models showed statistically highly significant correlation between predicted and observed penalty so that all of them can be used to explain how the penalty changes due to the physically measurable changes in impulsive sound.

However, closer look shows that Model 1 overestimates the penalty almost by E_M=2 dB. The largest overestimations occurred at large R_{on} and D_L values. All other models have their E_M values close to zero which means that there is no clear trend of overestimating or underestimating the penalty.

Models 2–5 provide similar E_M values, but Model 3 seems to have the largest individual errors (E_{min}, E_{max}). This scattering appears also as the smallest correlation coefficient.

DISCUSSION

This work is unique since previous studies have not compared different models for predicting the annoyance penalty of impulsive noise.

The analysis showed that Models 2, 4, and 5 were the most precise and they could be the most useful for real-life applications. Next, the applicability of these models is discussed from practical or engineer's viewpoint.

Models 1 and 2 presume that R_{on} and D_L (see Figure 1) must be determined for every impulse in sound. In this study, this was not needed since synthetic sounds were used in Ref. [1] and each impulse in an experimental sound was identical. However, this is not the case for real-life situations where subsequent impulsive sounds always carry very different R_{on} and D_L values. The analysis of long-term noise recordings may lead to massive amounts of impulse data. ISO 1996-3 does not advise how the R_{on} and D_L values obtained for subsequent impulses should be statistically treated. This leads to large reproducibility errors between different engineers with both Models 1 and 2.

Models 3 and 4 are based on the difference between maximum and minimum sound levels. Onset rate is not determined. These Models were successful because the observed penalties depended very much on level difference at all onset rates. Ignorance of onset rate seems to be justified for the experimental data of Ref. [1]. The challenge of Models 3 and 4 in real-life measurements is the same as for Models 1–2: impulsiveness must be measured for every impulse and some kind of statistical analysis is needed for the assessment of the long-term noise. This analysis is not advised in any regulation.

Table 2: Statistical descriptors of the prediction error E (M=mean, SD=standard deviation, min=largest individual negative error, max=largest individual positive error), and descriptors of the linear association between observed and predicted penalty (r_P=Pearsons' correlation coefficient, a=slope of linear fit, b=intercept of linear fit).

	Model				
	1	2	3	4	5
E_M	1.8	0.0	0.1	0.0	0.0
E_{SD}	1.6	0.8	1.3	1.1	1.1
E_{min}	-0.6	-1.8	-3.1	-2.2	-2.2
E_{max}	5.4	1.7	3.6	1.6	1.6
r_P	0.91	0.97	0.89	0.93	0.93
a	1.16	0.97	0.74	0.86	0.86
b	1.15	0.07	1.09	0.55	0.54

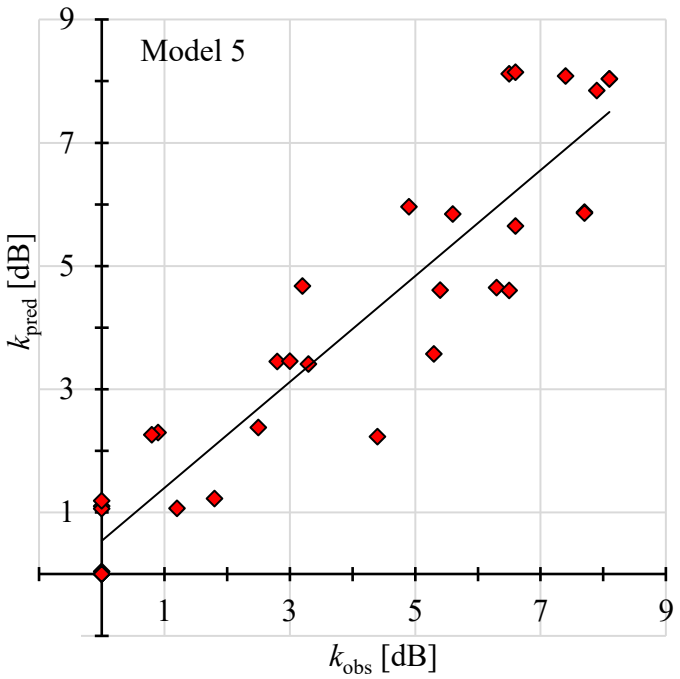

Figure 2: Association between the predicted penalty using Model 5, k_{pred}, and observed penalty based on the psychoacoustic experiment, k_{obs}.

Model 5 solves this problem since impulsiveness I_5 is a statistical parameter (L_{A1}-L_{A99}). Since the percentile sound levels L_{A1} and L_{A99} are available in most commercial sound level meters, it seems to be the easiest approach to use Model 5 in real-life noise measurements.

Because Models 3–5 ignore the onset rate, they may lead to erroneous results for intermittent sound scenarios where level differences are large, but onset rate is small (e.g., pass-by sound of individual vehicle). In such cases, subjective decision must be made that Models 3–5 should not be applied.

The weaknesses of this work are mostly related to experimental data. The outcomes of this work depended on the choices made in the design of the psychoacoustic experiment of Ref. [1] and the derived penalty values of Table 1. The experiment was originally conducted to assess the penalty model of ISO 1996-3. Therefore, it focused on the broad coverage of R_{on}

and D_L values. Because the ranges of both R_{on} and D_L were extremely broad, other features that impulsive noise in real-life can be, had to be strictly controlled. First, the impulses were synthetically created by modifying the time profile of pseudorandom noise. Second, the impulses were periodically presented with 2.5 second intervals. Third, the A-weighted SPL was 55 dB L_{Aeq} for all impulsive sounds. Real-life impulsive noises are only seldom fulfilling these limitations.

For example, there is recent evidence [6] that the annoyance penalty due to shooting noise (large R_{on}) agreed with Ref. [1] if L_{Aeq}=55 dB. However, the penalty values were significantly larger, when L_{Aeq}=35 dB. That is, penalties seem to increase by reducing overall sound level although the sound level profile of the impulse does not change.

Therefore, more experimental research should be conducted in the field of impulsive noise. Future studies should also focus on sound levels which are usual in residential environments: e.g., 25–35 dB (typical regulated indoor levels) and 35–55 dB (typical regulated outdoor levels).

CONCLUSIONS

This work showed that the noise annoyance penalty model of ISO 1996-3 overestimates the true penalty. This work provided an alternative model, which predicts the penalty better than ISO 1996-3, and it is based on sound level variability L_{A1}-L_{A99}.

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Pickleball: A growing source of community noise

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ABSTRACT

Pickleball, an increasingly popular racquet sport worldwide, produces a loud, distinct popping sound with each hit of the ball. A typical set of 4 outdoor pickleball courts may expose neighbors to more than 20,000 repetitive “pops” per day, several days a week. Even with doors and windows shut, pops are often audible inside nearby homes. A national online pilot survey of 264 communities, designed to purposefully explore the impacts on residents, found that pickleball noise negatively affects quality of life and leads to health concerns. A content analysis of public statements about the impacts of pickleball noise found that nearby residents may experience severe distress, trauma- or PTSD-like symptoms, anxiety, sleep disruption, and hearing “phantom” popping sounds in the absence of pickleball play. Chronic exposure to noise repeatedly activates the body’s stress response which may be exacerbated by other secondary stressors, like powerlessness to control the noise and conflicts between neighbors and players. Time-averaged A-weighted decibel metrics are not appropriate for assessing the impacts of this type of impulsive, high-event-rate noise. A multidimensional approach incorporating appropriate decibel metrics, number of noise events, duration of exposure, and relevant non-acoustic factors is required to understand the impacts of pickleball noise on health and quality of life.

INTRODUCTION

Pickleball is an increasingly popular racquet sport played worldwide with hard paddles and plastic balls that produce loud “pops.” These repetitive impulse sounds introduce a new and distinctive source of unwanted and potentially harmful noise in residential environments, exposing residents living near busy courts to thousands of sharp “pops” each day. An audio recording of the noise from 4 pickleball courts can be heard at Leahy [1].

In the US, more than 18,000 new courts were built in 2024 [2], exposing residents in many communities to repetitive impulsive noise The conflicts that have erupted over pickleball noise have been covered in hundreds of news reports, generated countless social media posts, and led to approximately 200 legal claims in the United States [3]. Similar issues are emerging in Singapore, Vietnam, Canada, India and Australia where the sport has also become popular. In the Netherlands, noise from padel, a similar racket sport producing repetitive impulse noise,

is subject to environmental noise regulations and has prompted the development of a padel-specific guidance document [4]. In Spain, a club owner was imprisoned for subjecting nearby residents to excessive noise from padel in violation of the country's legal noise limits [5].

Pickleball produces an impulsive sound when the racket makes contact with the ball. The sound has a rapid onset of 1-2 millisecond (ms) short duration that repeats, echoes, and reverberates in a high-density fashion for another 20 milliseconds, as shown in Figure 1 (Willis).

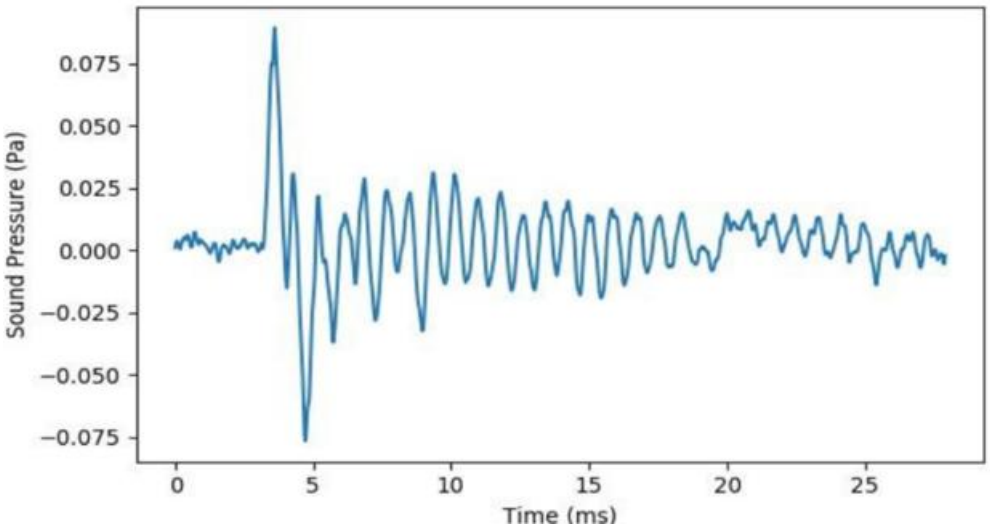

Figure 1: Pickleball noise pressure sound trace
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Pickleball pops have been measured courtside at 69.7 dBA Laeq, 92.2 dBA LAS max and 115.6 dBC Lcpeak [6]. Additional acoustic factors that may affect perception of pickleball noise include its spectral frequency (Hz), number of noise events, and cumulative exposure.

The pickleball pop captures listener attention, with an average peak frequency near 1200 Hz, similar to the frequencies used in vehicle backup alarms. Each busy court produces approximately 900 pops/hour [7]. Courts are often open 10-12 hours per day and a set of busy courts can produce more than 20,000 individual pops (noise events)/day, as shown in Figure 2.

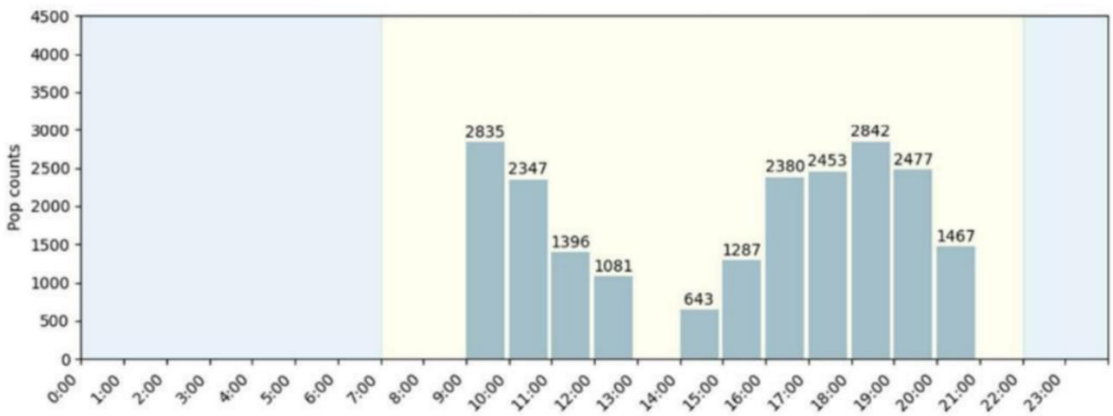

Figure 2: Pops per hour at 4 pickleball courts. 21,208 total pops in one day
Reproduced with permission from NoiseNet US Operations, Brisbane, Australia

Pickleball noise is a local, community experience. Apart from the sound that is generated, non-acoustic factors such as social conflict, perceived unfairness, or the residents' inability to quiet their homes may also contribute to adverse impacts of noise.

Few, if any, studies have examined the effects of long-term exposure to impulsive noise on the general public. This paper synthesizes findings from three recent studies to characterize the impacts of long-term exposure to pickleball noise: a content analysis of publicly reported health concerns [8], a pilot community survey of 264 impacted neighborhoods [9], and a thematic analysis of non-acoustic factors contributing to pickleball noise annoyance [10].

CONTENT ANALYSIS: SELF-REPORTED HEALTH CONCERNS

A large body of peer reviewed literature has firmly established the link between environmental noise and adverse health outcomes. Consistent with this, a recent content analysis of news articles, legal filings and social media posts found serious self-reports of physical and psychological health issues related to pickleball noise. See figures 3 and 4. People who spoke publicly about those health concerns frequently noted a sense of trauma, feeling tortured, and/or severe distress; two reports even mentioned suicidal thoughts related to the noise. Disrupted sleep, hearing phantom pops (i.e. hearing pops when no one is playing), elevated blood pressure and mental health concerns were other concerns frequently mentioned by residents living near courts [8].

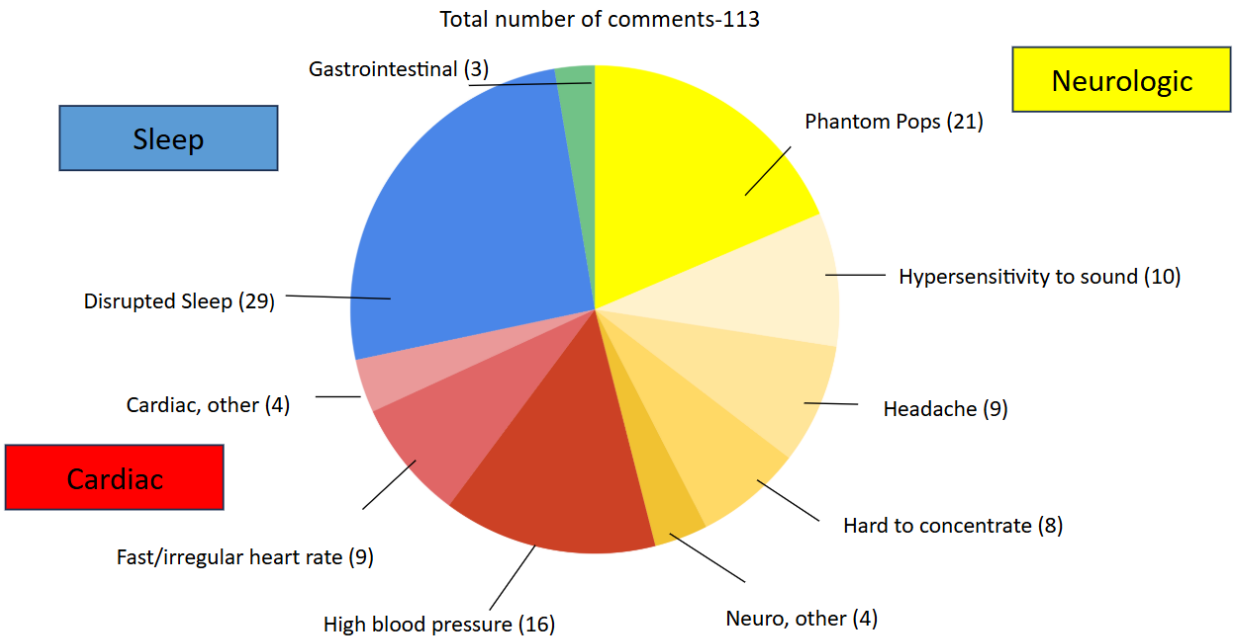

Figure 3: Self-reported physical symptoms from pickleball noise exposure

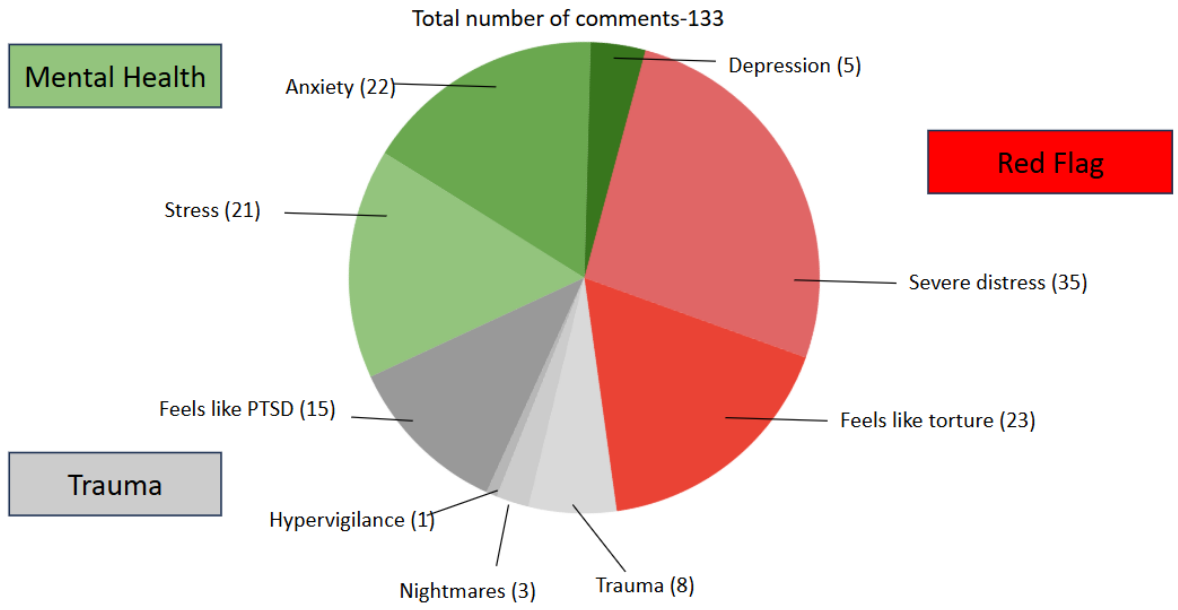

Figure 4: Self-reported psychological symptoms from pickleball noise exposure

COMMUNITY PILOT SURVEY

A community pilot survey of residents from 264 communities within 10-1000+ feet of pickleball courts evaluated impacts from pickleball noise on health, daily life, and community experience.

More than 90% of respondents reported health concerns related to pickleball noise. The most commonly reported health concerns included an intense emotional or physical reaction to the noise (70.3%), elevated blood pressure (60.5%), hearing phantom pops (58.4%), and disrupted sleep (50.9%).

Almost 8 in 10 (79.9%) respondents reported that pickleball noise frequently or always impacted their ability to feel calm at home. Nearly 3 in 4 (73.6%) reported they could hear the noise inside their home or workplace and close to 2 of 3 (64.0%) reported they could hear pickleball noise at night (after 6 pm). The majority (58.3%) of impacted residents reported potential exposure to more than 70 hours of pickleball noise per week at their homes.

Participants reported being unable to enjoy their homes, gardens, or outdoor spaces, and many have altered routines or even relocated to avoid the noise. Comments frequently describe an ongoing sense of intrusion— *"I cannot think, I cannot concentrate, I can't do anything in my house"* and a feeling that they are being driven indoors or away from home.

Some reported major life decisions such as delaying retirement or giving up hobbies, because of the noise. Over half of respondents have either already moved, want to move, or have moved part-time from their homes due to the noise.

The disruption from the noise affected relationships both at home and in the community. Almost 6 in 10 (58.8%) respondents reported stress on family relationships and almost 7 in 10 (69.9%) respondents reported stress on relationships with friends or neighbors due to the noise. Eight in 10 (81.2%) survey participants reported a loss of trust in authorities and more than 7 in 10 (72.4%) reported fear of being harassed for speaking out about the noise [9].

THEMATIC ANALYSIS: NON-ACOUSTIC FACTORS

A thematic analysis of public statements identified six recurring patterns of non-acoustic factors associated with pickleball annoyance and provided representative examples.

- inability to enjoy home and impact on daily activities
- perceived unfairness
- loss of trust in authorities
- social conflict and impact on interpersonal relationships
- perceived control
- fear

Residents frequently described being unable to enjoy their homes. One legal filing stated *"nearly 70% of ...waking hours are subject to the constant barrage"* while another resident described spending "*countless hours hanging around the local public library, thrift shopping, basically loitering...to stay away from home*".

Perceived unfairness and loss in trust is a recurrent theme expressed by residents as illustrated by a lawsuit claim: "*When presented with this clear evidence of community concern, (Parks and Rec) Director Holloway dismissively stated that the petition with 25 neighborhood signatures 'didn't mean anything to him' "*.

One media account documented ostracization and "*houses being graffitied, physical threats, and even a story of how someone used their car to nudge a woman for complaining"* while another resident described a neighbor having *"her brand-new tires slashed after speaking with pballers…. you really can put your safety at risk*" [10].

DISCUSSION

The reported health impacts from pickleball noise, (e.g., elevated blood pressure, sleep disturbance, anxiety and trauma-like responses) are consistent with extensive scientific evidence on the ability of noise to trigger the body's stress response. Noise stimulates the amygdala and activates the autonomic nervous system leading to inflammation and oxidative stress, resulting in damage to the vascular endothelium [11]. Chronic activation of this response increases the risk of cardiovascular, cerebrovascular, and metabolic harms as well as of mental health disturbances like anxiety and depression [12,13].

Impulse noise produces an "additional stress effect" compared with steady-state sound [14] and U.S. ANSI standards recommend a 5–12 dB penalty for impulsive noises [15]. Repeated exposure to unpredictable, uncontrollable impulsive sounds, such as pickleball, may amplify the physiologic stress response.

Many of the reported health effects from pickleball noise align with prior noise research, but some neurological and psychological effects may be more severe than previously reported. Hearing phantom pops may represent a trauma-related reactivity or a form of noise-induced tinnitus. For some, the phantom sounds are associated with sleep disruption and, for others, have lasted for weeks or months after moving away.

The potential for pickleball noise to trigger trauma-like responses warrants further consideration. Self-reported trauma or PTSD-like symptoms, along with frequent descriptions of "torture", severe distress, hypervigilance, and pickleball nightmares all suggest substantial responses to the noise. The most commonly reported health concern by survey respondents

was an intense emotional or physical reaction to the noise (70.3%), a question designed to screen for a possible trauma-like response. Concern about a trauma-like response is further validated by the two-thirds (66.0%) of survey respondents who reported extreme concern about impacts from pickleball noise on veterans and individuals with PTSD, the highest among vulnerable groups listed on the survey [9].

While research has demonstrated that non-acoustic factors can explain up to a third of the variation in noise annoyance [16], they may play an even larger role with pickleball, where the sound is personal, neighborhood-based, and discretionary. Pickleball noise substantially disrupts daily life for nearby neighbors, leading to loss of control over their acoustic environment, negatively impacting their interpersonal relationships, and contributing to social conflict. These factors and others may further heighten physiological stress responses, potentially contributing to adverse health outcomes.

While there is no published research evaluating the prevalence of noise impacts from pickleball, one California town recently surveyed all residents living within 500 feet of courts; 41.4% reported that the noise had negatively affected sleep, relaxation, work-from-home, or neighborhood experience [17]. These experiences are clearly very stressful and meet common definitions of an environmental nuisance, i.e., interference with the comfortable enjoyment of life or property.

WORKING TOWARDS SOLUTIONS

Effective mitigation of pickleball noise requires a multi-dimensional approach that reflects how communities actually experience sound. Decisions about court placement should extend beyond decibel levels to include lived experience.

Because pickleball noise is impulsive and repetitive, time-averaged A-weighted decibel metrics are not well suited to assessing its impacts. Appropriate metrics and considerations are required, recognizing that loudness alone is only a partial predictor of annoyance [18]. In fact, lowering the sound level does not lower annoyance levels if unpleasant sounds and/or patterns persist [19].

To fully explain the human impact of pickleball noise, additional acoustic characteristics must be considered, including impulsivity, frequency of events, irregularity, and total duration. Human response is also strongly influenced by non-acoustic factors, such as the inability to keep noise out of one's home, disrupted interpersonal relationships, and loss of trust in authorities.

These findings should inform policy decisions about both new and existing courts. Preliminary results from a detailed statistical analysis (in progress) of the community pilot survey show that increased setback distance provides the most consistent benefit, correlating with improved residential enjoyment. On the other hand, the survey results show that vinyl acoustic barriers which reduce decibel levels do not improve residents' ability to enjoy their homes. These findings suggest that policy should prioritize appropriate siting of courts and proactive efforts to reduce community conflict, with quieter equipment (e.g. rackets, balls) as a secondary, targeted measure.

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Passenger perception of train-induced noise and comfort on the M4 metro line in Istanbul

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ABSTRACT

This study examines passenger perceptions of train-induced noise and its implications for travel comfort on the M4 (Kadıköy–Sabiha Gökçen Airport) Metro Line in Istanbul. The research combines subjective passenger evaluations with in-situ acoustic measurements to provide an initial assessment of noise exposure within metro trains and station environments. An anonymous and voluntary questionnaire survey was conducted to gather information on passenger demographics, perceived noise levels, comfort conditions inside trains and on platforms, overall satisfaction with the acoustic environment, stated preference scenarios related to noise conditions, self-reported non-auditory effects such as fatigue or headaches, and individual coping strategies.

In parallel, A-weighted sound pressure levels were measured inside operating metro trains along the line on a station-to-station basis. The measured noise levels were approximately within the range of 50–70 dB(A), indicating moderate but noticeable exposure levels during normal operation. Additional measurements conducted at selected stations showed comparable sound levels during train arrival and departure phases.

Preliminary findings suggest that train-induced noise exposure varies spatially along the corridor, likely influenced by local infrastructure characteristics and operational conditions. A general consistency was observed between subjective passenger perceptions and the measured noise levels, indicating that noise exposure plays a meaningful role in perceived comfort and annoyance. By integrating passenger feedback with field measurements, this study provides initial insights into the acoustic experience of metro users and highlights the importance of considering user perception in noise assessment and management strategies for urban rail systems.

INTRODUCTION

Urban rail systems are essential components of sustainable metropolitan transportation because they provide high-capacity mobility, reduce dependence on private car use, and support efficient movement within dense urban areas. In addition to their mobility benefits, metro systems contribute to the urban environment by reducing surface traffic pressure, air

pollution, and road-based transport demand. However, the acoustic environment of metro systems remains an important passenger-comfort issue, particularly in underground and enclosed rail environments where users are exposed to train-induced noise during both onboard travel and platform waiting periods [1].

Transportation noise is widely recognized as an environmental factor affecting human health and well-being, with annoyance representing one of the principal outcomes used in environmental noise assessment. The World Health Organization identifies long-term annoyance and self-reported sleep disturbance as relevant health effects of environmental noise exposure, while railway noise recommendations are commonly discussed using indicators such as Lden and Lnight [2]. Accordingly, noise and vibration in railway and metro environments should be considered not only as physical exposure parameters but also as factors influencing annoyance, communication, fatigue, satisfaction, and overall travel comfort [3].

Metro noise originates from several interacting mechanisms, including wheel–rail interaction, rail roughness, train speed, tunnel geometry, track structure, aerodynamic effects, vibration transmission, and onboard equipment. As these factors vary along a corridor, passengers may experience changing acoustic conditions between stations. Previous studies show that wheel–rail roughness, corrugation, train speed, track type, tunnel sections, and both airborne and structure-borne transmission paths significantly influence in-train noise levels [4].

Underground metro environments may generate particularly high noise exposure because tunnel surfaces, enclosed geometries, curves, gradients, and slab-track systems can intensify sound propagation and reflections. In the Greater Cairo Metro, interior coach noise was strongly influenced by tight curves, reflective tunnel surfaces, unballasted slab track, coach location, and window conditions, highlighting the importance of evaluating operational and infrastructural factors together [5]. Environmental vibration studies further show that train-induced vibration propagates through the track, tunnel, soil, and surrounding structures, requiring source–path–receiver based assessment of both vibration and noise impacts [6].

The relationship between railway noise, vibration, and human response extends beyond onboard environments. Studies near rail corridors indicate that vibration may increase perceived disturbance and that conventional noise mapping may underestimate annoyance when sources such as braking, squeal, whistles, screeching, and operational activities are excluded [7]. Research on structure-borne noise also demonstrates that train-induced vibration can generate low-frequency indoor noise and that structural vibration is positively related to structure-borne noise levels relevant to human comfort [8]. Furthermore, a combined annoyance model for subway-induced structural vibration and ambient noise showed that vibration and noise should be evaluated together because human response includes both subjective uncertainty and individual variability [9]. Field studies similarly confirm that structure-borne noise from subway operations can exceed acceptable limits and cause substantial annoyance, making vibration-to-noise transmission an important design consideration [10].

For passengers, interior metro noise is directly related to acoustic comfort and travel experience. A study on the Beijing Metro reported a significant positive relationship between equivalent sound pressure level and subjective annoyance, suggesting that metro interior noise should not exceed approximately 84–85 dB(A) to provide an acoustically comfortable environment [4]. Similarly, in the Guangzhou Metro, more than half of surveyed passengers reported being disturbed by noise, with wheel–rail squeal identified as one of the most annoying sources. The same study also found that noise and vibration levels vary across metro lines and that passengers are generally more sensitive to noise and vertical vibration than to horizontal vibration [11].

Although A-weighted sound pressure level is widely used in railway and metro noise assessment, previous research suggests that acoustic comfort cannot be fully explained by dB(A) values alone. Studies on high-speed train comfort indicate that subjective parameters are necessary to understand passenger perception and that A-weighted SPL may not adequately represent the frequency components to which passengers are sensitive [12]. Psychoacoustic research further shows that perceived loudness is more strongly correlated with annoyance than A-weighted sound pressure level, supporting the use of perception-based indicators alongside conventional physical metrics [13].

The need to integrate objective and subjective indicators has also been emphasized in metro-specific research. The Metronova project in Oslo demonstrated that physical measurements alone are insufficient to explain complaints and perceived disturbance, and that vibration measurements, questionnaire surveys, interviews, psychoacoustic parameters, and laboratory listening tests can provide a more comprehensive understanding of metro noise perception [14]. These findings indicate that passenger-centered metro noise assessment should combine in-situ acoustic measurements with subjective evaluations such as perceived loudness, annoyance, comfort, communication difficulty, and satisfaction.

Metro stations should also be considered part of the overall acoustic experience of metro travel. Their enclosed geometry, reflective surfaces, ventilation systems, and material properties may affect reverberation time, sound pressure distribution, and speech transmission. In underground stations, the use of sound-absorbing materials on both ceilings and sidewalls has been shown to improve acoustic conditions and speech intelligibility, which is particularly important for public address systems and emergency communication [1]. Therefore, platform noise exposure during waiting, train arrival, and departure periods should be evaluated together with in-train exposure.

Noise mitigation studies indicate that railway noise and vibration control requires interventions throughout the source–path–receiver chain. Barrier-based approaches may reduce airborne noise and ground-borne vibration, while track-based solutions such as vibration-damping fasteners, rubber pads, floating slab systems, rail grinding, and rail dampers can influence both environmental vibration and interior noise [3]. However, mitigation effectiveness should be evaluated not only through physical noise reduction but also through changes in annoyance, communication conditions, and passenger comfort [6].

In Türkiye, railway noise studies have primarily focused on environmental noise regulation, strategic noise mapping, action planning, community annoyance, and railway corridor impacts. A case study from Istanbul emphasized the role of environmental noise regulations, noise maps, action plans, and questionnaires in identifying community disturbance near railway lines [15]. However, studies specifically examining passenger perception of train-induced noise in Turkish metro systems remain limited, particularly those combining in-train and station measurements with passenger-reported comfort, annoyance, satisfaction, and non-auditory effects.

Therefore, the M4 Kadıköy–Sabiha Gökçen Airport Metro Line provides a relevant case for examining how measured train-induced noise levels correspond to passenger perceptions of acoustic comfort. This study presents an initial assessment of passenger perception of train-induced noise and its implications for travel comfort on the M4 Metro Line. The research combines an anonymous passenger questionnaire survey with in-situ A-weighted sound pressure level measurements conducted inside operating metro trains and at selected station environments. Unlike studies relying solely on physical noise indicators, the study evaluates measured acoustic exposure together with perceived noise levels, comfort conditions, acoustic satisfaction, stated preferences, self-reported effects such as fatigue and headache, and individual coping strategies. By integrating objective measurements with 107 passenger survey responses, the study contributes to a more user-centered understanding of acoustic

comfort in urban rail systems and supports future noise assessment and management strategies for metro environments.

METHODOLOGY

Survey Design and Data Collection

A questionnaire-based survey was conducted to examine passenger perception of train-induced noise and its effects on travel comfort on the M4 Kadıköy–Sabiha Gökçen Airport Metro Line in Istanbul. The survey was designed as an anonymous and voluntary user-response study and supported by in-situ acoustic measurements. This combined approach was adopted because previous metro noise studies indicate that passenger annoyance and acoustic comfort should be evaluated using both measured sound levels and subjective user responses [4].

The questionnaire focused on four main dimensions: perceived noise level, comfort and annoyance, self-reported effects, and behavioral response. Respondents evaluated noise perception inside trains and at station platforms, communication difficulty, comfort reduction, acoustic satisfaction, and non-auditory effects such as headache, fatigue, stress, and reduced concentration [2, 9].

Most perception-based questions used five-point Likert scales, where higher scores represented stronger perception, greater annoyance, lower comfort, or higher importance. Multiple-choice and multiple-response questions were used for symptoms, coping behaviors, and travel preferences. This structure enabled the evaluation of both scalar perception trends and frequency-based passenger responses. The inclusion of subjective indicators is consistent with previous research showing that A-weighted sound pressure level alone may not fully explain passenger acoustic comfort [12].

A total of 107 respondents participated in the survey. Data were collected in two field stages in February and March 2026. The first stage focused on perceived noise level, annoyance, comfort reduction, communication difficulty, and acoustic satisfaction, while the second stage added travel behavior, coping strategies, and stated preference questions. Responses were collected inside operating metro trains, on station platforms, and in other M4-related travel contexts.

During the March field campaign, the main survey locations were Yakacık Adnan Kahveci, Bostancı, Göztepe, and Ayrılık Çeşmesi stations. These locations were selected because they represent different passenger densities, urban functions, and travel conditions along the M4 corridor. Since metro passengers experience noise both inside trains and in station environments, platform-related responses were also included in the assessment [1, 5].

Acoustic Measurements

In-situ acoustic measurements were conducted under normal operating conditions to provide an objective reference for the acoustic environment experienced by passengers on the M4 Kadıköy–Sabiha Gökçen Airport Metro Line. The measurements complemented the questionnaire data and supported the interpretation of passenger perception, annoyance, and travel comfort [4, 11, 14].

The acoustic survey focused primarily on train interior noise along the M4 corridor. A-weighted sound pressure levels were measured inside operating metro trains on a station-to-station basis between Pendik and Kadıköy, since metro interior noise may vary between adjacent sections depending on train speed, wheel–rail interaction, rail roughness, track condition, tunnel geometry, curve radius, and vehicle-related transmission mechanisms [4–6].

Measured peak A-weighted sound pressure levels ranged between 51.4 dB(A) and 68.4 dB(A), indicating spatial variability along the corridor. The highest values were recorded between Acıbadem and Ayrılık Çeşmesi, suggesting that this section may represent a local acoustic hotspot. These measurements were considered indicative field data reflecting passenger acoustic experience during regular metro operation rather than long-term exposure indicators.

Additional platform-based reference measurements were conducted at Pendik station during train arrival and departure. The measured levels were 56.7 dB(A) and 56.5 dB(A), respectively. Platform measurements were included because metro stations are acoustically complex enclosed spaces where geometry, reflective surfaces, reverberation, and material selection may influence sound pressure distribution and speech intelligibility [1, 2].

Overall, the measurements were used as supporting field data rather than as a standardized noise-mapping or compliance assessment. The main objective was to determine whether measured sound levels varied along the corridor and whether these variations were broadly consistent with passenger-reported perceptions.

Data Processing and Analysis

The questionnaire responses and acoustic measurement data were analyzed using descriptive and comparative statistical methods. Frequency distributions, percentage shares, and mean values were calculated for perceived noise level, annoyance, comfort reduction, communication difficulty, acoustic satisfaction, perceived importance of noise, and stated preference for improved acoustic conditions. Likert-scale responses were comparatively evaluated to identify dominant trends in passenger perception and travel comfort [4, 11, 14].

For multiple-choice and multiple-response items, response frequencies were calculated to identify the most frequently reported non-auditory effects and coping strategies. Symptoms such as fatigue, headache, stress, and reduced concentration, together with behaviors such as headphone use, were evaluated as part of the broader passenger experience [2, 12, 13].

Survey responses were also examined with reference to field stage and approximate location. Timestamp records and field notes were used to group responses into indicative station or corridor sections, allowing exploratory comparisons between different parts of the M4 line. Since the survey was not designed as a controlled exposure–response experiment, these comparisons were interpreted as indicative rather than definitive [1, 5].

The acoustic measurement results were organized on a station-to-station basis and compared with passenger perception patterns where possible. Particular attention was given to whether sections with higher measured A-weighted sound pressure levels were associated with stronger perceived noise, annoyance, or comfort reduction. Accordingly, train-induced noise was evaluated not only as an engineering parameter but also as a user-centered environmental factor affecting comfort, satisfaction, and travel behavior [4, 7, 9].

By combining 107 questionnaire responses with in-situ acoustic measurements, the analysis aimed to determine whether the measured acoustic environment of the M4 line was reflected in passenger-reported comfort, annoyance, satisfaction, and behavioral response, and to identify sections where future noise management strategies may be most relevant.

RESULTS AND DISCUSSION

Passenger perception of in-train noise and annoyance

The survey results indicate that train-induced noise is a clearly noticeable component of the passenger experience on the M4 Kadıköy–Sabiha Gökçen Airport Metro Line. For perceived noise inside trains, the mean score was 4.11 out of 5, based on 106 valid responses. In total,

72.4% of respondents rated in-train noise perception as 4 or 5, while 42.9% selected the maximum score. These findings suggest that train interior noise is not perceived merely as a weak background condition, but rather as a dominant acoustic feature of the journey.

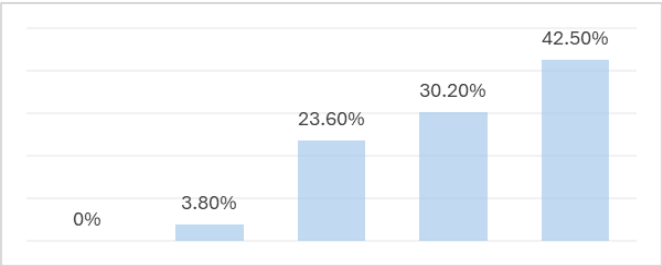

Figure 1: Distribution of perceived in-train noise level, Likert scale 1–5.

This finding is consistent with previous metro noise studies showing that interior train noise is an important determinant of passenger acoustic experience. Ma, M. et al. reported that metro interior noise has become a growing concern for passengers and drivers, and that passenger annoyance is significantly associated with averaged equivalent sound pressure level in metro tunnel sections [4]. Similarly, Li, X. et al. found that noise and vibration inside metro trains directly affect passenger comfort and annoyance, with more than half of surveyed passengers in Guangzhou Metro reporting disturbance from noise. Therefore, the high perception scores observed in M4 survey support the interpretation that train-induced noise should be evaluated not only as a physical exposure, but also as a user-centered service quality issue [11].

Annoyance levels were also high, although slightly lower than perceived noise scores. The mean annoyance score was 3.83 out of 5, with 60.0% of respondents selecting 4 or 5. This difference between perception and annoyance is important. It suggests that passengers may clearly notice the noise, but not all passengers translate this perception into the same level of discomfort. This may reflect habituation, necessity-driven tolerance, differences in individual noise sensitivity, or variation in travel purpose and journey duration.

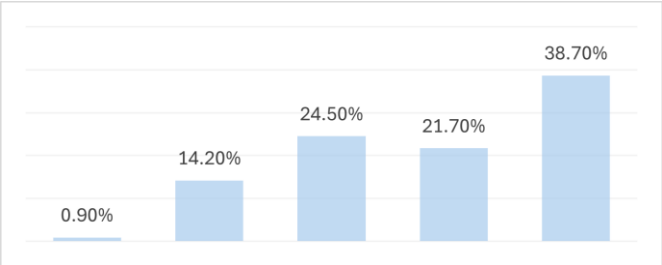

Figure 2: Distribution of annoyance caused by in-train noise, Likert scale 1–5.

The relationship between perceived noise and annoyance was also supported by correlation analysis. The Spearman correlation coefficient between in-train noise perception and annoyance was $\rho = 0.605$, indicating a strong positive association. In other words, passengers who perceived train noise more strongly were also more likely to report higher annoyance. This result is consistent with the exposure–response logic adopted in previous studies, where subjective annoyance is evaluated together with measured or perceived acoustic exposure [4, 11]. It also supports the argument that annoyance is not random, but closely linked to perceived acoustic intensity.

Communication difficulty and travel comfort

One of the strongest findings of the survey concerns communication difficulty. The mean score for the item asking whether train noise makes speaking or phone communication difficult was 4.10 out of 5. Moreover, 78.1% of respondents selected 4 or 5, and 54.3% selected the

maximum score. This indicates that train-induced noise affects not only subjective comfort, but also everyday functional activities, especially speech communication and phone use.

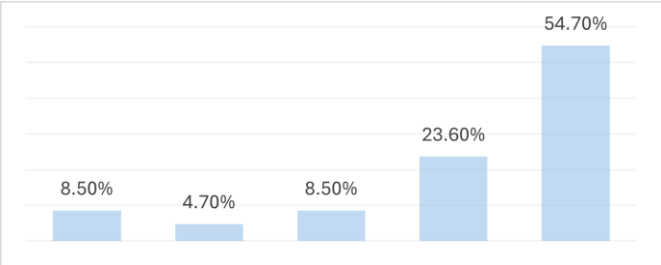

Figure 3: Distribution of communication difficulty due to train noise, Likert scale 1–5.

This result is particularly relevant because acoustic comfort in transport environments is not limited to perceived loudness or annoyance. It also includes the ability to communicate and understand announcements. Sü, Z. and Çalışkan, M. emphasized that metro stations are acoustically problematic spaces and that speech intelligibility is a critical issue, particularly in enclosed rail environments. Although their study focused on station acoustics, the same broader principle applies to the in-train environment: poor acoustic conditions can reduce the functional quality of passenger experience [1].

The correlation between in-train noise perception and communication difficulty was also strong ($\rho = 0.579$). This suggests that passengers who perceive higher in-train noise are more likely to report difficulty in speaking or using the phone during travel. This finding strengthens the interpretation that the acoustic environment of the M4 line affects practical travel conditions, not only subjective annoyance.

Noise also had a clear effect on overall travel comfort. In total, 81.6% of respondents stated that noise reduces their travel comfort either significantly or to some extent. More specifically, 50.5% reported that noise “significantly reduces” comfort, while 31.1% stated that it reduces comfort “to some extent.” Only 14.6% reported no effect. These results show that acoustic conditions inside trains are directly related to perceived travel quality.

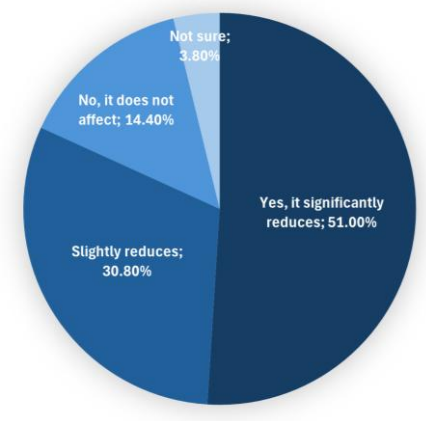

Figure 4: Effect of train noise on travel comfort.

Previous studies support this interpretation. Letourneaux, F. et al. argued that acoustic comfort in trains cannot be fully represented by physical sound pressure level alone, because subjective factors must also be considered [12]. Poisson, F. and Boullet, I. further showed that annoyance is strongly correlated with perceived loudness and that this relationship may be stronger than the relationship between annoyance and dB(A) [13]. Therefore, the high comfort-reduction scores in the M4 survey suggest that passengers evaluate noise through a perceptual process that extends beyond measured sound level alone.

Standing passengers showed a more complex pattern. When asked whether standing makes noise more disturbing, 45.2% reported that it makes no difference, while 30.8% stated that noise is more disturbing when standing. This suggests that standing does not always increase perceived annoyance directly, but it may increase the overall comfort burden associated with noise exposure.

Operational conditions associated with increased noise perception

Passengers were also asked when in-train noise becomes more noticeable. The most frequently selected condition was acceleration, reported by 70.5% of the respondents. This was followed by approaching stations with 32.4%, and braking with 26.7% of the respondents.

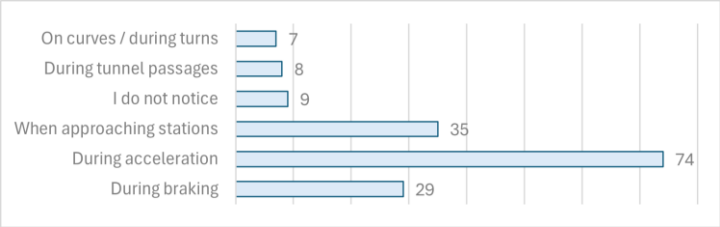

Figure 5: Operational conditions where noise becomes more noticeable.

These findings suggest that passengers associate noise mainly with dynamic operating phases rather than with a constant background condition. Acceleration appears to be the dominant perceived noise event inside the train. This may be related to traction noise, wheel–rail interaction, vibration transmission, and changes in vehicle speed. Ma, M. et al. noted that metro interior noise is influenced by operational and infrastructure-related factors such as train speed, track type, rail wear, and curve radius. Eldakdoky, S. and Elkhateeb, A. also reported that noise levels inside metro coaches can be affected by alignment conditions, tunnel characteristics, track structure, coach location, and window conditions. These studies support the interpretation that passengers may identify specific operating phases as acoustically more intrusive [4, 5].

Journey duration also played a major role in annoyance. 44.2% of respondents stated that noise annoyance increases significantly as journey duration becomes longer, and 31.7% said that it increases slightly. Together, 75.9% of respondents reported at least some increase in annoyance with longer travel time.

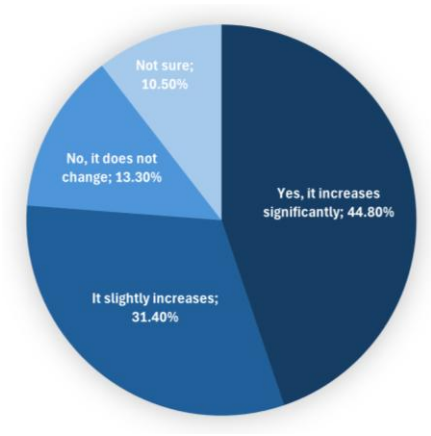

Figure 6: Effect of journey duration on noise annoyance.

This result supports the interpretation that in-train noise has a cumulative character. Unlike platform noise, which is often dominated by short peak events during arrival and departure, train interior noise is experienced continuously during the journey. Therefore, even moderate

sound levels may become more disturbing as exposure duration increases. This distinction is important because many passengers use the line for relatively long corridor-based trips.

Non-auditory effects and passenger well-being

The survey results indicate that in-train noise is associated with several self-reported non-auditory effects. The most frequently reported effect was headache, selected by 48.1% of the respondents. These results are important because they show that metro noise is perceived not only as an acoustic discomfort issue, but also as a factor related to passenger well-being. The World Health Organization identifies environmental noise as an important public health issue with negative effects on health and well-being [2].

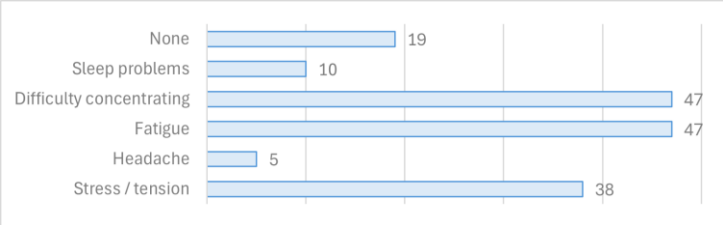

Figure 7: Self-reported non-auditory effects of in-train noise.

Although the present study does not clinically measure health outcomes, the high frequency of self-reported headache, fatigue, reduced concentration, and stress suggests that passengers associate the M4 acoustic environment with everyday well-being effects. These findings should therefore be interpreted cautiously as self-reported perceptions rather than medical diagnoses. However, they remain valuable because they reflect how passengers experience noise during daily travel. Similar to the user-centered approach emphasized by Ma, M. et al. and Li, X. et al., the results show that subjective responses provide important insight into the practical impact of metro noise on passengers [4, 11].

1.1. Coping behavior and passenger adaptation

Passengers appear to actively adapt to the acoustic conditions inside the M4 trains. The most common coping strategy was listening to music with headphones, reported by 70.2% of the respondents. By contrast, 26.9% of the respondents stated that they do not take any specific action. This finding is a strong behavioral indicator. Headphone use may partly reflect a general travel habit, but in the context of high perceived noise and high communication difficulty, it may also function as a way of masking or reducing perceived acoustic discomfort. The fact that such a large proportion of respondents use headphones suggests that passengers are not simply accepting the sound environment passively; rather, they are trying to manage it individually.

This result also points to a service quality issue. If passengers rely on personal coping strategies to make the acoustic environment more tolerable, current in-train acoustic conditions may not be fully satisfactory from a comfort perspective. This interpretation aligns with previous research emphasizing that passenger perception must be considered in addition to objective sound measurements when evaluating acoustic comfort in trains [12, 13].

1.2. Satisfaction, service quality, and perceived need for noise reduction

Passenger satisfaction with current train noise levels was relatively low, with a mean satisfaction score of 2.37 out of 5. This indicates that the existing acoustic conditions of the M4 trains are not perceived positively by many passengers. At the same time, noise was considered an important component of overall service quality, with a mean importance score of 3.80 out of 5. This suggests that passengers do not regard noise as a minor issue, but as one of the factors shaping their evaluation of metro travel comfort.

The perceived need for noise reduction was also strong. Most respondents stated that noise reduction is necessary or partly necessary, indicating broad support for acoustic improvement on the M4 line. When asked about possible solutions, passengers most frequently referred to better sound insulation in train vehicles and improved rail and train maintenance. These preferences are consistent with previous findings showing that metro interior noise can be influenced by wheel–rail interaction, rail roughness, track characteristics, alignment, and vehicle-related transmission mechanisms [4, 5]. Therefore, the results suggest that both vehicle-based and infrastructure-based measures should be considered in future noise mitigation strategies.

Travel behavior and modal preference

Noise also appears to have an influence on passenger travel behavior. More than half of the respondents reported that noise affects their preference for public transport either directly or partly. This indicates that metro noise is not only a comfort-related issue, but also a factor that may influence how passengers perceive the attractiveness of public transport.

However, most respondents continue to use the M4 line despite the noise. The main reasons were time savings and habituation to the existing acoustic conditions. This suggests that continued use of the line should not be interpreted as full satisfaction with the noise environment. Instead, it may reflect the functional advantages of the M4 line, such as travel time, route convenience, and lack of better alternatives.

The results also suggest that acoustic improvement could have a positive effect on passenger attitudes toward the line. A considerable share of respondents stated that they would use the M4 more frequently if noise levels were reduced. In addition, many passengers perceived the M4 as noisier than alternative public transport modes on similar routes. Overall, these findings indicate that noise reduction may contribute not only to passenger comfort, but also to the perceived quality and attractiveness of metro travel.

Spatial variability along the corridor

The in-situ measurements showed that train interior noise levels varied along the M4 corridor, with peak A-weighted sound pressure levels ranging from 51.4 dB(A) to 68.4 dB(A). The highest measured values were observed between Acıbadem and Ayrılık Çeşmesi, suggesting that local track, tunnel, alignment, or operational characteristics may influence noise exposure inside trains. This finding is consistent with previous metro noise studies showing that interior noise does not remain constant along a line. Li, X. et al. reported non-uniform noise and vibration distributions along Guangzhou Metro lines, while Ma, M. et al. emphasized that metro interior noise may vary depending on train speed, route radius, track type, and rail condition. Similarly, Eldakdoky, S. and Elkhateeb, A. showed that alignment characteristics, tunnel geometry, track structure, coach location, and window conditions can affect noise levels inside metro coaches [4, 5, 11].

The survey data also supported an indicative spatial interpretation. Responses collected during the field campaign showed variation across different station/time blocks, with relatively high perceived noise and annoyance values around Bostancı, Göztepe, and Ayrılık Çeşmesi. Although the survey-based spatial grouping was exploratory, the high annoyance observed near Ayrılık Çeşmesi is broadly consistent with the higher measured noise levels in the Acıbadem–Ayrılık Çeşmesi section.

Overall, these results suggest that train-induced noise exposure on the M4 line may include localized acoustic hotspots rather than a uniform corridor-wide condition. However, the relationship between measured sound levels and passenger annoyance should not be interpreted as strictly one-to-one, since subjective response may also be affected by individual sensitivity, crowding, trip purpose, travel duration, and expectation. More detailed section-

based measurements would be useful in future studies to better identify the operational and infrastructure-related causes of spatial variation.

CONCLUSION

This study examined passenger perception of train-induced noise on the M4 Kadıköy–Sabiha Gökçen Airport Metro Line by combining questionnaire responses with in-situ acoustic measurements. The findings indicate that in-train noise is not perceived as a minor background condition, but as a significant component of the travel experience affecting annoyance, comfort, satisfaction, and communication. This is consistent with previous studies showing that interior noise is closely associated with passenger annoyance and that noise and vibration levels vary according to operational and infrastructure-related conditions [4, 11, 14].

The results further show that the effects of metro noise extend beyond acoustic comfort. Passengers reported communication difficulty, reduced travel comfort, headache, fatigue, reduced concentration, and stress, suggesting that in-train noise should be considered within a broader passenger well-being framework. This interpretation is supported by environmental noise research identifying noise as a public health and quality-of-life issue, as well as railway studies indicating that noise and vibration may act as combined stressors influencing annoyance and subjective response [2, 3, 7, 9].

An important finding is the cumulative nature of in-train noise exposure. Many respondents reported that annoyance increases with journey duration, indicating that continuous exposure may be as important as short-term peak levels. Since train interior noise is experienced throughout the journey, while platform noise is generally associated with shorter events, metro acoustic comfort assessments should consider both exposure duration and passenger perception. This is consistent with studies showing that acoustic comfort cannot be fully explained by A-weighted sound pressure levels alone and is also influenced by perceived loudness, low-frequency components, source characteristics, and subjective annoyance [5, 12, 13].

The in-situ measurements confirmed that train interior noise varies along the corridor, with the highest peak A-weighted sound pressure levels recorded between Acıbadem and Ayrılık Çeşmesi. Survey responses showed similar tendencies, suggesting that certain sections may function as acoustic hotspots. Previous studies likewise associate spatial variations in train-induced noise with speed, curve radius, rail roughness, track condition, tunnel geometry, slab-track systems, vehicle condition, and wheel–rail interaction [4–6, 8].

Passenger behavior should not be interpreted solely through continued use of the line. Although many passengers continue to use the M4 because of travel-time advantages and limited alternatives, most respondents supported noise reduction measures and indicated that improved acoustic conditions could increase metro use. Therefore, noise reduction may contribute not only to acoustic comfort but also to perceived service quality and the attractiveness of public transport [2, 15].

Overall, the findings demonstrate that metro noise should be approached as a multidimensional issue involving acoustics, passenger satisfaction, well-being, and travel behavior. Potential mitigation measures include improved vehicle sound insulation, rail grinding, wheel and rail maintenance, targeted interventions in high-exposure sections, and station-level acoustic treatments where platform exposure and speech intelligibility are critical [1, 10, 16].

Future studies should include larger passenger samples, repeated measurements under different operating conditions, and more detailed section-based analyses. In particular, speed, acceleration, braking, curve radius, rail condition, tunnel geometry, passenger density, and

station acoustic properties should be examined together to better explain spatial variations in noise exposure and their effects on passenger well-being and travel behavior [2, 4, 14].

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Impact of Noise of an Air-Source Heat Pump on Daytime Functioning: Annoyance, Concentration, and Relaxed Attentiveness in an Imaginative Everyday-Situation Experiment

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ABSTRACT

This study examined the impact of air-source heat pump (AHP) noise on daytime annoyance, concentration, and mood (relaxed attentiveness) in healthy adults. Using an imaginative everyday-situation approach in a cross-over study design, 40 participants (21 female, 19 male) read Greek myths during two 15-minute conditions: (1) no noise (baseline condition) and (2) outdoor-recorded AHP noise, filtered as heard through a tilted window ($L_{Aeq,indoor}$ = 30 dB). Responses in the AHP noise condition were compared with those at baseline. Annoyance was assessed with the ICBEN 5-point verbal scale adapted to the task, while concentration difficulties and relaxed attentiveness were measured via a set of questionnaire items. Noise annoyance was significantly higher during the AHP noise condition than during baseline. Relaxed attentiveness was also significantly reduced during the AHP noise condition. No overall main effect emerged for concentration difficulties; however, sequence effects indicated that participants reported greater difficulty when the AHP noise condition preceded the baseline condition, suggesting that the subsequent silence may have facilitated restored concentration. Overall, AHP noise impaired daytime functioning by increasing annoyance and reducing relaxed attentiveness during reading. These findings underscore the need for further research on the effects of AHP noise on daytime functioning and well-being in residential settings — an issue of growing importance as heat pump installations expand to support the rapid energy transition required to address human-made climate change.

INTRODUCTION

The rapid expansion of heat pump technology, driven by policies aimed at decarbonising the residential heating sector, has substantially increased the number of air-source heat pumps (AHPs) installed in urban and suburban settings across Europe and beyond [1]. Whilst AHPs

represent a significant step forward in terms of energy efficiency and climate protection, their widespread deployment in densely populated residential areas has brought a new source of environmental noise into close proximity to dwellings, gardens, and outdoor living spaces.

AHPs operate via an outdoor unit — a fan-driven compressor — that runs intermittently throughout the day and night. The resulting noise is characterised by tonal and broadband components, including low-frequency content associated with compressor operation and higher-frequency aerodynamic fan noise.

Research on the health and well-being effects of AHP noise remains comparatively sparse relative to the extensive literature on road traffic, railway, and aircraft noise. Existing field studies have indicated that residents exposed to nearby AHP noise report elevated levels of annoyance and difficulties relaxing and concentrating. Those reporting higher AHP noise annoyance also mentioned more psychosocial symptoms [2]-[3]. However, the effects of modern AHP on daytime activities, particularly on the ability to concentrate, to relax, and to maintain a state of calm attentiveness during ordinary indoor tasks, have received limited systematic investigation in controlled experimental conditions.

The present study employed an *imaginative everyday-situation* approach, in which participants were asked to engage in a reading task during two noise conditions (no noise vs. AHP noise) whilst imagining themselves at home [4]. The primary aim was to determine whether AHP noise exposure significantly affects noise annoyance, concentration disturbance, and mood (attentiveness) during a reading task in healthy adults. The study described in this paper is part of a study combining multi-night polysomnography (PSG) and daytime testing to assess the effects of AHP noise at daytime and during the night. Findings on the impact of AHP noise on sleep are presented in [5]. The full combined study is described in detail in [6]-[7].

METHODS

Study Design and Participants

The study employed a cross-over, double-blind laboratory design using an imaginative everyday-situation paradigm. Forty healthy adults (21 female, 19 male; mean age 37.4 years) participated in the experiment. Participants in this study had previously participated in a study on the effects of nocturnal AHP noise on sleep and were recruited from an existing volunteer database. They were screened for the following inclusion criteria: normal hearing, no sleep disorders, no current use of psychoactive medication, and no self-reported diagnosis of a noise-related disorder (see [5], [7] for more details). Noise sensitivity was assessed in a screening survey prior to the study using a single item within a set of four items on the sensitivity towards environmental burden such as odour, weather, noise, and environmental stress in general; participants were characterised as having on average moderate noise sensitivity (M = 3.17, SD = 1.17, 5-point scale from 1 [not] to 5 [very]).

Acoustic Stimuli and Playback

The acoustic stimulus consisted of a 15-minute scenario derived from outdoor recordings of a commercially available 11.2 kW AHP unit under real-life operational conditions. The scenario incorporated distinct operational phases: switch-on, load change transitions, steady-state continuous operation, and switch-off. The recorded signal was spectrally filtered to simulate transmission through a tilted window, yielding an indoor equivalent continuous A-weighted sound pressure level ($L_{\mathrm{Aeq,indoor}}$) of 30 dB at the participant's seating position. Playback was achieved via loudspeakers arranged to produce a sound field that replicated the perceptual character of environmental noise entering from outdoors. In the quiet baseline condition, no

acoustic stimulus was played; residual ambient noise in the laboratory room was 18 to 22 dB $L_{Aeq,indoor}$.

Experimental Task and Procedure

Each participant completed two 15-minute experimental sessions in counterbalanced order: one in the AHP noise condition and one in the quiet baseline condition. To standardise the cognitive task, participants were instructed to read excerpts from a collection of Greek myths. They were asked to imagine themselves sitting in their own home whilst performing this task, thereby contextualising the experimental exposure within a plausible everyday indoor scenario. This imaginative everyday-situation approach has been used in prior AHP noise research to enhance ecological validity whilst maintaining experimental control [4]. The order of conditions was counterbalanced across participants: half experienced the baseline first (Baseline → Noise), and half experienced the noise condition first (Noise → Baseline). Between the two sessions and after the second session, participants completed a short questionnaire. The questionnaire includes questions on noise perception in the laboratory room, the assessment of noise annoyance using the ICBEN 5-point scale [8], difficulties in concentrating on the text by means of two items to be answered on a 5-point rating scale ("I had to read the text several times to understand it.", "It strained me to read the text."; Cronbach's Alpha = 0.84 for baseline and 0.88 for AHP noise condition), and mood (relaxed attentiveness) with three items to be rated on a 5 point scale (1 [not] to 5 [very]) ("I am relaxed", "I am alert", "I am distracted" [recoded]; Cronbach's Alpha = 0.73 for baseline and 0.75 for AHP noise condition). The two latent concepts 'difficulties in concentrating on the text' and 'mood (relaxed attentiveness)' were derived from a principal axis factor analysis (PFA) – see [7] for more details. A fanless tablet (Terra Pad 1161, Wortmann AG, Hüllhorst, Germany) was used for presenting the texts, questionnaires, and instructions. The participants, as well as the experimenter, were not informed of the specific research hypotheses and the order of the experimental conditions.

RESULTS

Table 1 shows the results of the comparison between the baseline and AHP noise conditions regarding noise annoyance, difficulties in concentrating on the text and mood (relaxed attentiveness). In comparison to the baseline condition, noise annoyance is higher, and the relaxed attentiveness lower in the AHP noise condition. Overall, there is no difference in the difficulties in concentrating on the text between the two experimental conditions.

Table 1: Comparison of annoyance, difficulties in concentrating on the text and mood in experimental conditions (median and nonparametric Wilcoxon test results)

Variable	**Median in baseline condition**	**Median in AHP noise condition ($L_{Aeq,indoor}$ = 30 dB)**	**Z**	**p**
Noise annoyance	1.0	2.0	-4.48	< 0.001
Difficulties concentrating on the text	3.0	3.0	1.24	0.216
Mood (relaxed attentiveness)	4.33	3.67	-3.02	< 0.001

Z = Wilcoxon test score statistic, p = significance level

However, for the difficulties in concentrating, subgroup sensitivity analyses revealed an effect of the order of the experimental conditions: Difficulties in concentrating were higher in the AHP noise condition (Median = 2.5) compared to baseline (Median = 1.5) when the noise condition was prior to the baseline condition (sequence B). In the subgroup of participants exposed to the sequence A '(1) Baseline – (2) Noise' the difficulties in concentrating was considerably higher, but not different between the two conditions (Median = 3.5) – see Figure 1. The results indicate that the exposure to AHP noise impairs the concentration on the text more when subjects experienced silence in the experimental condition prior to the noise condition, whereas silence following noise exposure may facilitate the restoration of attentional resources.

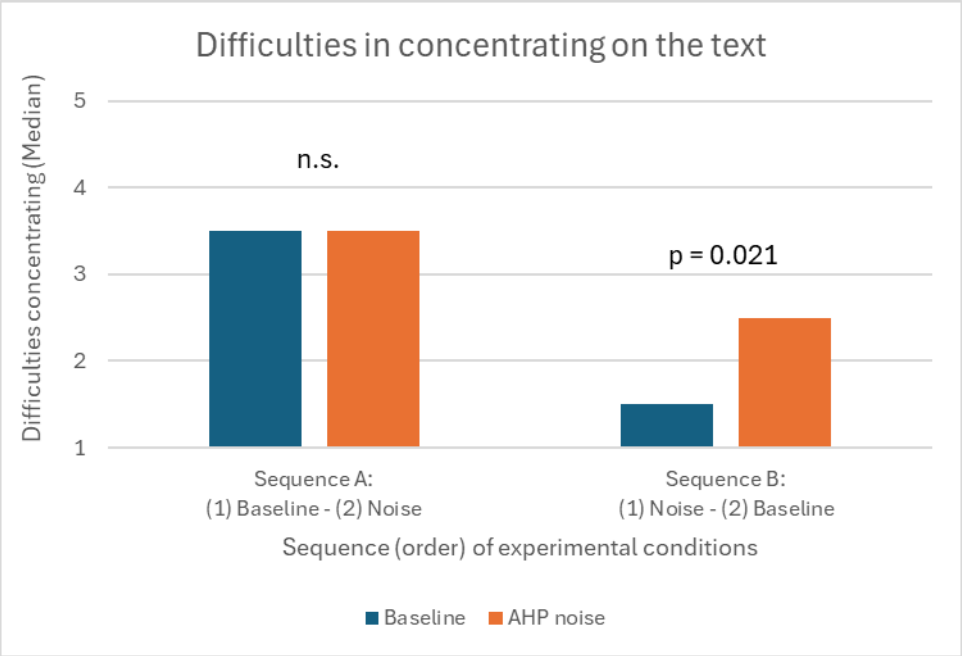

Figure 1: Difficulties in concentrating on the text in baseline versus AHP noise conditions in subgroups of different sequencies (order) of the experimental conditions

Further subgroup analyses show that noise annoyance was higher and the mood (relaxed attentiveness) poorer in the noise condition in all age groups except for the group of 50 to 65 years (Bonferroni-adjusted $p > 0.017$). The effect of the noise condition on annoyance persists independent of the gender, order of the experimental conditions, and the degree of noise sensitivity. No noise-condition effect on annoyance was observed when subjects were exposed to the tilted-window condition the previous night before the daytime experiment (Bonferroni-adjusted $p > 0.017$). Low noise-sensitive subjects reported more difficulties in concentration (Bonferroni-adjusted $p < 0.025$), an effect that did not occur for high-sensitive participants (Bonferroni-adjusted $p > 0.025$). The noise-condition effect on mood (relaxed attentiveness) did not reach statistical significance for males across subgroups exposed to different sequences of experimental conditions, noise-sensitivity subgroups, and subgroups exposed to different experimental conditions the study night prior to the daytime experiment ($p >$ Bonferroni-adjusted level of significance).

The reported findings of the subgroup analyses should be interpreted with caution given the relatively small subgroup sample sizes and the exploratory nature of these analyses.

DISCUSSION AND CONCLUSIONS

The present study provides experimental evidence that AHP noise at an indoor level of 30 dB L_{Aeq} significantly impairs two important dimensions of daytime well-being: noise annoyance and relaxed attentiveness during a reading task.

These findings are consistent with previous research by [9], who reported that ventilation noise levels of approximately 40 dB(A) were perceived as moderately disturbing when participants imagined a workplace acoustic environment. In addition, nocturnal exposure to low-frequency noise (LFN) has been associated with increased irritability the following morning [10]. The present results further corroborate field studies indicating that low-frequency noise generated by heat pumps and ventilation systems may adversely affect concentration and cognitive performance, including reading-related tasks [3], although the latter effect did not reach statistical significance in this study.

The absence of a statistically significant overall main effect of the noise vs. baseline conditions on concentration difficulties is itself informative. It may suggest that, in the experiment, participants attempt to maintain their cognitive concentration, albeit at the cost of noise annoyance and mood (here: emotional engagement with the task). This is in line with previous research results indicating no impact of noise on cognitive performance at the cost of aftereffects such as annoyance [11].

The finding that silence following noise facilitated improved concentration performance is consistent with the Attention Restoration Theory [12], which proposes that involuntary attentional demand imposed by urban noise depletes cognitive resources, and that exposure to quiet, restorative environmental situations enables recovery of directed attention, even in in a short 15-minute period of silence following AHP noise like in the present study. The sequence effect may also reflect a short-term change effect, where a shift in noise exposure elicits an exaggerated response in the direction of the change, particularly when exposure increases [13]-[14]. Similarly, the growing number of complaints associated with newly installed air-source heat pumps (AHPs) in rural areas may be attributable to the pronounced contrast with previously quiet acoustic environments. As urban densification continues, the increasing deployment of AHPs in residential areas is likely to contribute to higher overall environmental noise exposure. Beyond potential impacts on sleep and reading performance, elevated noise levels may also interfere with speech communication and everyday functioning. The rising prevalence of remote and home-based work further highlights the public health relevance of these disturbances.

Several limitations of the present study should be acknowledged. First, the controlled laboratory setting, whilst enabling precise acoustic exposure control, may not fully capture the complexity of real-life exposure conditions. In residential settings, individuals are exposed to AHP noise for extended periods, potentially with concomitant variations in attitude towards the source, perceived habituation, and varying task demands. Second, the reading material employed (Greek myths) was selected for its standardisation and neutrality but was reported by some participants to be unfamiliar or challenging, which may have influenced baseline concentration levels independently of acoustic conditions. Third, the sample was restricted to healthy adults with moderate noise sensitivity; the responses of more noise-sensitive individuals, elderlies, children, or those with health vulnerabilities may differ substantially.

Socio-acoustic and epidemiological field studies are recommended to examine annoyance, cognitive functioning over time and potential cumulative effects on well-being. The potential moderating impact of individual and contextual (non-acoustic) factors such as noise sensitivity, attitudes towards heat pumps, and sociodemographic factors warrant further examination in larger samples.

To conclude, two controlled laboratory studies with 40 subjects investigated the effects of AHP noise exposure on sleep and daytime activities [7]. This paper present findings on the impact of AHP noise on daytime activities, the results on the impact of AHP noise exposure on sleep are described in [5]. Regarding daytime activities, the study showed that AHP noise increase annoyance, partly impairs self-reported concentration during routine activities such as reading, and impairs subjects' mood, specifically the relaxed attentiveness, i.e. the emotional engagement with the task. The continued expansion of AHPs and other sustainable energy technologies in residential environments, together with increasing home-based work and urban densification, highlights the growing relevance of environmental noise exposure and the need for effective sound insulation measures. As climate-friendly heating and ventilation systems become more widespread, greater attention should be paid to acoustic design of AHPs and residential buildings. The present findings suggest that even moderate AHP noise exposure may adversely affect concentration, attentiveness, and annoyance. Accordingly, residential planning and building regulations should incorporate appropriate noise mitigation strategies, including consideration of standards for low-frequency noise emissions.

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The surveys on health effect of aircraft noise caused by the change of nighttime flight restrictions for Narita International Airport

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ABSTRACT

In this paper, the new project on health effect of aircraft noise for residents living around Narita International Airport has been started because of the change of nighttime flight restrictions for the A-runway since 2019. The questionnaire survey on health effects was carried out before the change of nighttime flight restrictions for the A-runway in 2019, and the questionnaire survey after the change of nighttime flight restrictions finished in 2025, in order to grasp health outcomes caused by the change of nighttime flights. Between these two questionnaire surveys, another additional survey was performed under unusual environment impacted by the COVID-19 pandemic. The participants of three cross-sectional surveys in this project involved common in partial. The health outcomes of these surveys involved psychological effects like noise annoyance, night-time insomnia, mental effects like nervous and depressive tendency, and physical effects like high-blood pressure. In addition, we have investigated the sleep effect study for a part of the questionnaire respondents by using an objective method after the questionnaire survey in 2025, in order to assess relationships between human reactions and nighttime aircraft noise events. Based on these questionnaire surveys, the health effects of aircraft noise caused by the change of nighttime flight restrictions on Runway-A would be analyzed comprehensively from both longitudinal and cross-sectional statistical models. The objective sleep effects would be complementary to the assessment of subjective sleep effects derived from statistical models. The progress of this project until 2025 is reported in this paper.

INTRODUCTION

Since the opening in 1978, Narita International Airport, a large-scale inland airport, has evolved with the local community around the airport. At the opening, the airport was equipped with a single runway (Runway-A), and a parallel runway (Runway-B) was constructed to keep pace with increased demand for air transport in 2002. Both the expansion of Runway-B by 1,000 m and the construction of Runway-C would be performed for the capacity enhancement of the airport. Against the increase of aircraft noise exposure caused by those increases of the

airport capacity, Narita International Airport Corporation (NAA) has carried out various noise countermeasures, that is the mitigation of noise sources, the improvement of airport structure, and community countermeasures [1]. However, the demands for a project on the health effects of aircraft noise became to grow under these circumstances, and it resulted that Narita Airport, Community Council and Civil Aviation Bureau had agreed to perform the project on health effects of aircraft noise for residents living around the airport.

This new project would investigate longitudinal aspects of health effects and have a plan to survey a health outcome related to nighttime aircraft noise using an objective method [2]. From the necessity of both scientific knowledge and equality to implement the project on the health effects surveys, the NAA established the committee that consisted of academic experts and chiefs of local government to both remain in control of and get reports of each survey. The ethics committee of Kobayasi Institute of Physical Research approved this project, and all participants confirmed their consent for project participation.

A NEW PROJECT ON THE HEALTH EFFECTS FOR AIECRAFT NOISE

The targets of the project

This new project was designed to investigate the health effects of aircraft noise for residents around the airport before and after the changing nighttime flight restrictions on Runway-A, in order to grasp health outcomes caused by the change of nighttime flights. This project entails a longitudinal design [3-7] with a different from the previous cross-sectional ones on the health effects [8-9].

This project was based on the survey using a questionnaire to investigate psychological, mental and physical effects against aircraft noise. In order to investigate from view of longitudinal aspects, the participants of the surveys performed before and after the changing nighttime flight restrictions on Runway-A involved common in partial. In addition, sleep monitoring against nighttime aircraft noise was first investigated using an objective method.

The questionnaire surveys of health outcomes on aircraft noise

Before the change of nighttime flight restrictions for Runway-A on October 27th in 2019, the first survey (Survey-1) was carried out from September 1st to October 15th in 2019 under control of the committee. The survey areas consisted of “exposure areas” surrounding the airport (thin red broken lines of Fig. 1) and “control area” where are adjacent to the airport but have not affected by aircraft noise exposure (black dotted lines of Fig. 1). The Survey-1 using the questionnaire performed for around 3,600 participants aged from 20 to 79 years old lived in both exposure and control areas.

However, the survey planned after changing nighttime flight restrictions, it was respited until recover of aircraft demands because of dramatically decreased flight movement due to the COVID-19 pandemic as shown in Figure 2. It took more than a few years to recover sufficiently such significant decrease caused by the impact of COVID-19 which spread from the beginning of 2020. Figs 3 and 4 show histories of aircraft movement ratio and level difference of noise indices (L_{den}, $L_{\mathrm{Aeq,22h\text{-}07h}}$) to referred the fiscal year of 2019 at the typical monitoring positions as shown in Fig 1. The nighttime aircraft number and nighttime noise index at two monitoring positions in the Runway-A side increased continuously since 2019, but it appeared remarkably influence of the COVID-19 in other aircraft numbers and noise indices. It has resulted in performing the survey after the change of nighttime flight restrictions (Survey-3) in the fiscal year of 2025. As aspect of longitudinal study, 7,000 participants in Survey-3 were also included those in Survey-1.

The noise impact zone has expanded under the Noise Prevention Law on March 24th in 2020 (red thick lines in Fig. 1). Therefore, additional survey (Survey-2) was performed between October 1st and November 19th in 2021 under unusual environment impact caused by the COVID-19 pandemic. 5,000 participants in Survey-2 were included those in Survey-1. The questionnaire could be also answered by internet since Survey-2. The results of the Suvey-2 might be important to grasp influence on the expansion of the noise impact zone, and unexpected effects caused by unusual environment impact due to the COVID-19 pandemic.

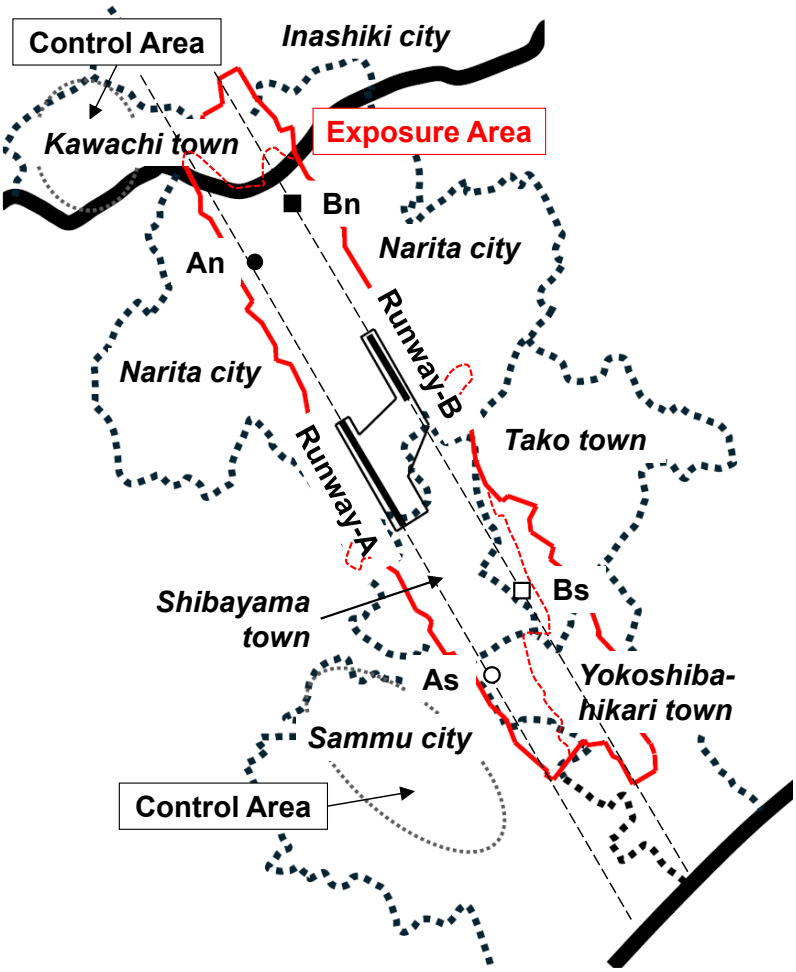


Figure 1: The survey area of the new project and four typical monitoring positions (An, As, Bn, Bs).

The common questionnaire

Three questionnaire surveys have been performed between 2019 and 2025 as part of the project on the health effect survey are shown in Table 1. Each survey on health effects of aircraft noise for residents living around the airport was carried out by collecting a postal or postal and internet questionnaire. The questionnaire consisted of a general questionnaire asking about living environment developed by INCE/Japan [10], questionnaire dedicated to sleep effects [11], important questions asking about noise sensitivity (WNS-6B) [12], information on individuals (gender, age, BMI (height and weight), occupations, habits of smoking and drinking, residence year, hours at home, sleeping time, systolic/diastolic blood pressure et al.) and house environment. Using a part of THI questionnaire [13,14], it was assessed in terms of 18 subjective symptoms summing-up to the following stress scales: Depression (DEPR) and Nervousness (NERV).

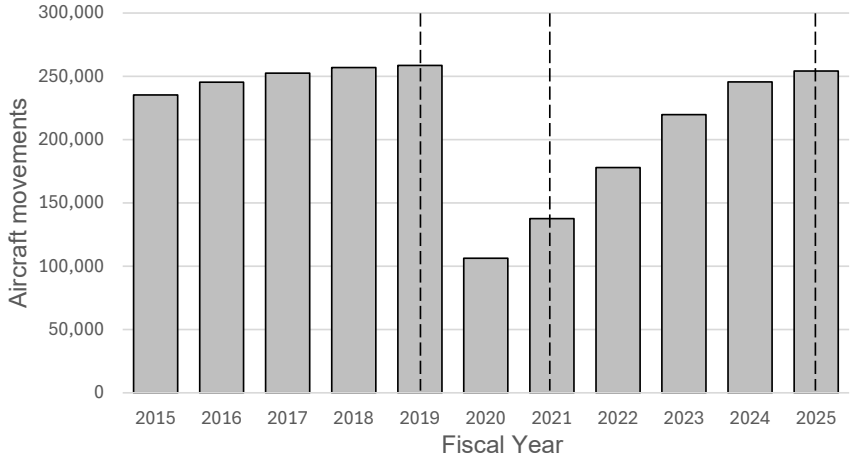
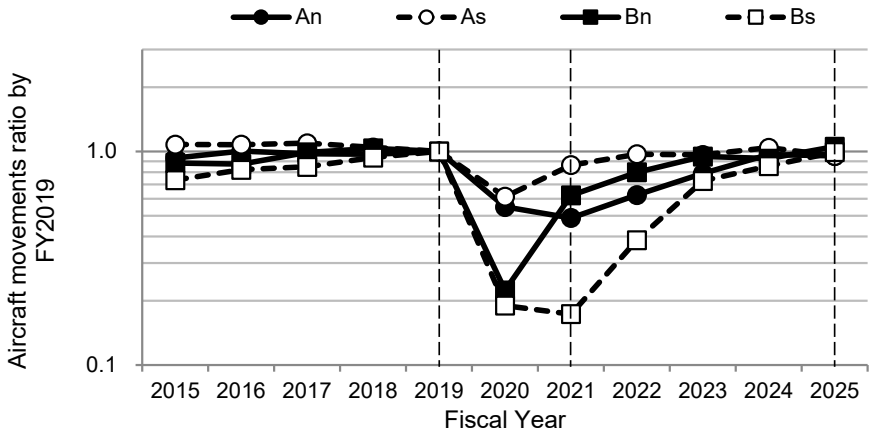
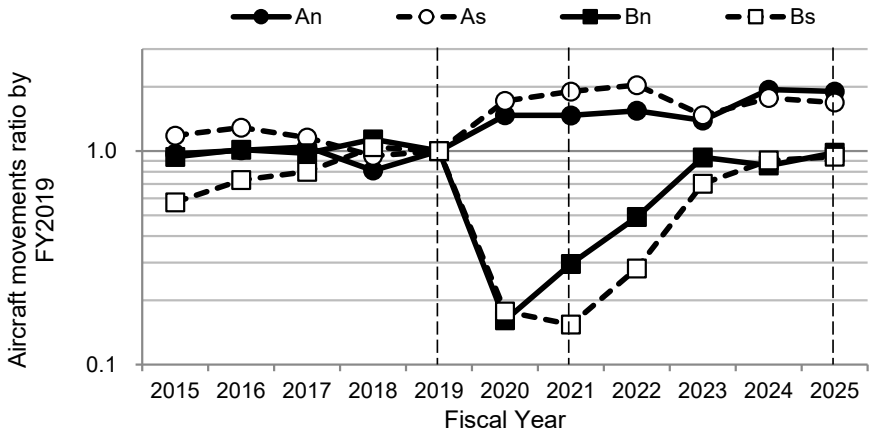


Figure 2: History of total aircraft movements between 2015 and 2025 at Narita International Airport

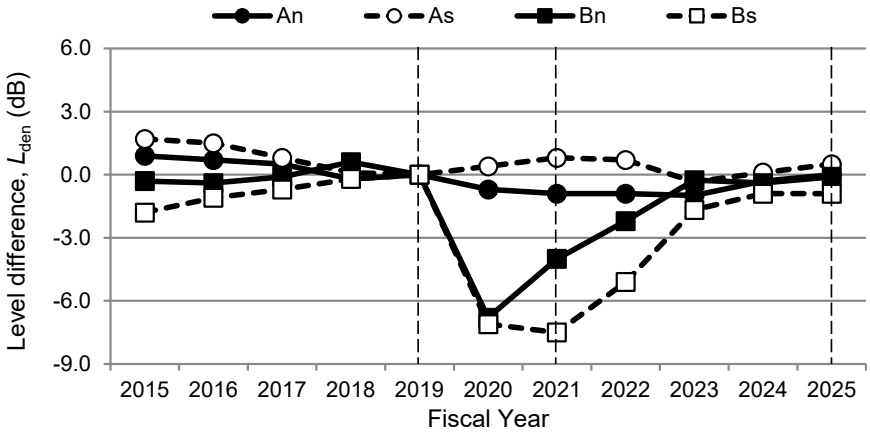


Total Number of aircraft movement per fiscal year

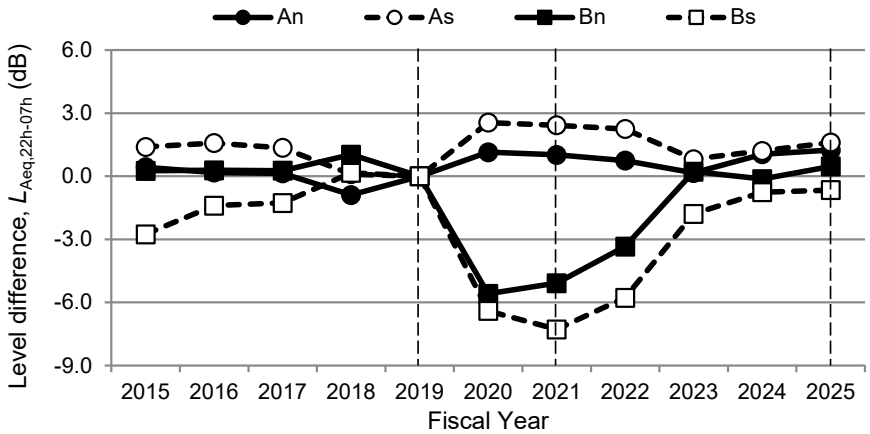


Nighttime number of aircraft movement per fiscal year

Figure 3: History of aircraft movement ratio to referred FY2019 at the typical measurement positions.



Noise Exposure Index, L_{den}



Noise Exposure Index, $L_{Aeq,22h\text{-}07h}$

Figure 4: History of level difference to referred FY2019 at the typical measurement positions.

Table 1: Comparisons of three surveys during 2019 to 2025 in the new project.

	Survey-1 in 2019	Survey-2 in 2021	Survey-3 in 2025
Period	Sep. 1 to Oct. 15	Oct. 1 to Nov. 19	Oct. 1 to Nov. 14
Procedure	By postal mail	By postal or internet	
Method	Self-reported questionnaire		
Gender	Male and Female		
Age	20 to 79 years old		
Participants Num.	3,659	5,000*	7,000*
Health outcomes	Psychological effects (noise annoyance, life disturbance, stress), physical effects, nighttime sleep effect (sleep disturbance)		
Individual conditions	Noise sensitivity, Body mass index (BMI), Occupations, Habits of smoking and drinking, Residence year, Hours at home, Sleeping time, Noise insulation work		

*) including common participants of the Survey-1 in 2019.

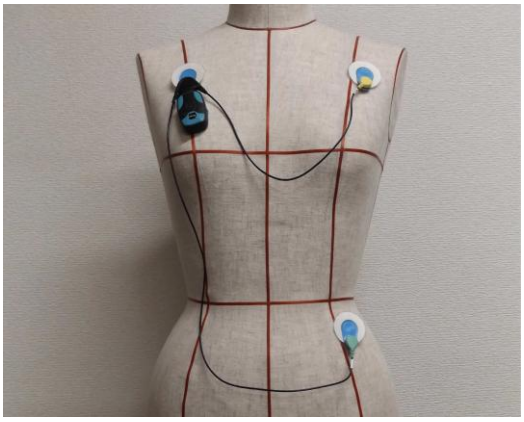
Sleep monitoring survey using an objective method

The purpose of sleep monitoring survey is to measure objectively the short-term effect against aircraft noise events (ANE) during sleep in real-life condition. The physical impact of ANEs on human sleep would be assessed by both actigraphy (wGT3X-BT, ActiGraph USA) [15] and ECG device (FAROS 180, Bittium Finland) [16] as shown in upper part of Figure 4. The former was recorded arm movement continuously for every time sequence (e.g. 1 min), and the latter was collected a full ECG provided to measure heart rate validity (HRV). In addition, night-related subjective evaluation was performed using morning sleep logs, that is OSA sleep inventory MA version [17].

Before implementing the sleep monitoring survey, the preliminary examination was carried out for some staff of the survey in a detached house in the vicinity of the monitoring position “Bn” shown in Fig. 1 at the middle of May in 2025. As shown in the lower part of Fig. 4, the noise monitoring devices were set up both outside and inside of the detached house. We verified simultaneous measurement of both human monitoring and noise monitoring devices at this preliminary examination. The procedures of the sleep monitoring survey to decrease local support of technical staff as simple as possible were also checked.

The participants of the sleep monitoring survey were recruited from respondents of Survey-3. We selected from many applicants with consideration for individual conditions, that is sensitive to noise, relationship between sleep time and operation hours of the airport, attitude to aircraft noise, and so on. The sleep monitoring survey was implemented in each participants’ house from about the first of December in 2025 to the middle of April in 2026.

Actigraphy (wGT3X-BT)



ECG device (FAROS 180)

Outdoor noise monitoring

Indoor noise monitoring

Figure 4: Human sleep monitoring devices and outdoor / Indoor noise measurement settings.

The fundamental result of questionnaire surveys

Comparisons of the fundamental results among three cross-sectional surveys (Survey-1 to 3) show in Table 2. The respondent ratio of each survey is around 50 % or above, female respondents seem to be greater than male ones. However, the respondents aged in their sixties or above account for a half of total ones, those by internet may make an impact to increase respondent ratio in their fifties or below.

With respect to the long-term effects of aircraft noise on psychological, physical, sleep effect, self-reported questionnaires were obtained from three surveys between 2019 and 2025 with residents in the vicinity of Narita International Airport. A series of these surveys would be analyzed comprehensively based on statistical models. Moreover, the results of the sleep monitoring survey for nighttime aircraft noise using objective method might give a supplementary explanation as to those of questionnaire survey. The health outcomes against aircraft noise would be just discussed on the committee carefully with both subjective and objective aspects.

Table 2: Comparisons of respondent characteristics among three cross-sectional surveys.

	Survey-1 in 2019	Survey-2 in 2021	Survey-3 in 2025
Participants Num.	3,659	5,000*	7,000*
Respondents' ratio	51.8 %	58.9 %	48.9 %
Respondents in each zone	(Procedure by) Postal vs Internet 100% -	(Procedure by) Postal vs Internet 80.9% 19.1%	(Procedure by) Postal vs Internet 70.6% 29.4%
	(Gender) Female vs Male 51.6% 48.4%	(Gender) Female vs Male 52.6% 47.4%	(Gender) Female vs Male 49.6% 50.4%
	(Age groups) 20s 2.6% 30s 8.6% 40s 13.6% 50s 16.6% 60s 27.0% 70s 31.6%	(Age groups) 20s 5.0% 30s 9.1% 40s 14.7% 50s 17.2% 60s 26.1% 70s 27.9%	(Age groups) 20s 6.4% 30s 9.2% 40s 14.2% 50s 17.8% 60s 24.4% 70s 28.0%
	(L_{den}) Ctrl. <57dB ≧57dB 16.8% 43.3% 39.9%	(L_{den}) Ctrl. <57dB ≧57dB 17.2% 64.8% 20.0%	(L_{den}) Ctrl. <57dB ≧57dB 17.5% 48.5% 34.0%
	($L_{Aeq,22h\text{-}07h}$) Ctrl. <45dB ≧45dB 16.8% 43.2% 40.0%	($L_{Aeq,22h\text{-}07h}$) Ctrl. <45dB ≧45dB 17.2% 35.8% 47.0%	($L_{Aeq,22h\text{-}07h}$) Ctrl. <45dB ≧45dB 17.5% 25.6% 56.9%

*) including common participants of the Survey-1 in 2019.

CONCLUSIONS

The new project on health effects of aircraft noise, based on the agreement for airport capacity enhancement among Narita Airport, Community Council and Civil Aviation Bureau, was performed for residents living around Narita International Airport. This project is based on a longitudinal study with different point on view from previous ones. In order to investigate health

effects before and after the change of nighttime flight restrictions, the questionnaire survey have been performed three times between 2019 and 2025.

The first survey (Survey-1) on the health effect survey has been carried out from September to the first half of October in 2019, before changing nighttime flight restrictions for Runway-A. The survey after changing nighttime flight restrictions for Runway-A (Survey-3) started on October in 2024, and completed on April in 2025. Between these two surveys, additional survey (Survey-2) was performed to grasp unexpected effects on the project caused by unusual environmental impact by the COVID-19 pandemic. In addition, in Survey-3 of 2025, sleep monitoring by nighttime aircraft noise has been investigated using an objective method. Both actigraphy and ECG devices were used to measure human response during sleep, and outdoor and indoor noise events were simultaneously monitored by sound level meters.

The results obtained from both questionnaire surveys and sleep monitoring have been just discussed by the committee carefully. The subjective data of questionnaire survey would be analyzed based on longitudinal and cross-sectional statistical models. It would be hoped that the objective data obtained from sleep monitoring survey gave a supplementary explanation as to subjective sleep disturbance by questionnaire survey.

Acknowledgements

We gratefully acknowledge all the members of the committee for their thoughts and comments while working on this project. This paper represents a review of the scientific literatures undertaken by the corresponding author and co-authors. It does not represent a consensus view of the committee and/or NAA.

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Exploring the Concept of Fair and Equitable Distribution to Minimise Social Unacceptability of Airspace Design Options

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ABSTRACT

Airspace modernisation has increased pressure to demonstrate that changes to aircraft routes are not only operationally efficient, but also fair and more publicly acceptable. However, “Fair and Equitable Distribution” (FED) is frequently referenced without a shared definition or a practical method for evaluating alternative design options. This paper presents findings from the FED2 study examining how people judge fairness when the distribution of aircraft noise changes, and how distributional evidence can better inform engagement and decision-making. The research combined distributional noise assessment with qualitative community engagement. It used a virtual airport to minimise location-based bias, enabling 13 community focus groups to compare a baseline conventional design with four alternative lateral distribution concepts. Results show that perceived distributional fairness is driven less by equal sharing in principle and more by the scale and location of change relative to existing noise patterns, for the participants in this study. Participants expressed strong concern about newly overflown areas, impacts conflicting with tranquility or land-use expectations, and changes perceived as disproportionate or insufficiently justified. Previous social justice research distinguished three different forms of fairness: distributional, procedural, and informational/interactional. Our work suggested that trust and acceptability depended not only on predicted noise changes, but on how clearly trade-offs, uncertainty and concentrated burdens were communicated, and whether engagement was experienced as genuine rather than consultative. The work proposes a practical FED framework to support more human-centred airspace decision-making, improve accountability, and help prioritise mitigation and engagement where the relative risk of social unacceptability is greatest.

INTRODUCTION

The UK is undertaking a substantial programme of airspace modernisation, intended to make better use of performance-based navigation and improve the efficiency, capacity and resilience of the airspace system [1, 2]. For airports and airspace change sponsors, this creates a practical and social challenge. Routes may be designed and flown more accurately, but this can concentrate noise over smaller areas or introduce aircraft noise into places where

people have little previous experience of overflight. Airspace design therefore has to address not only aggregate noise outcomes, but also the perceived fairness of who experiences change and why.

Around Gatwick Airport, the idea of fair and equitable dispersal or distribution (FED) was introduced in 2015 as an aspirational objective by communities affected by aircraft noise and has subsequently been discussed through Gatwick's Noise Management Board. The FED1 study, commissioned by Gatwick Airport Limited on behalf of the Noise Management Board, did not simply seek to prescribe a preferred pattern of sharing. Rather, it reviewed the policy, regulatory and process context for aircraft noise and airspace design; identified potential technical and procedural options; considered acoustic, health and non-acoustic metrics; and explored how FED might be evaluated within the airspace change process [3].

Importantly, FED1 concluded that no clear definition then existed that would enable airspace managers and aircraft operators to design solutions to meet the FED objective. It therefore proposed a conceptual framework in which relevant non-acoustic factors, soundscape requirements, acoustic and psychoacoustic metrics, health considerations, operational metrics and performance indicators would be developed with stakeholders through consultation or co-creation. FED1 recommended further work to develop a detailed operational method, grounded in real-world aviation scenarios and technical feasibility. The FED2 study reported here was designed as that next step: an empirical study of how distributional changes are understood by communities and how these insights might be translated into a practical assessment and engagement framework, with the full report published as CAP2971 [4].

The overall aim of FED2 was to understand how airspace design options influence those features that shape perceptions of fairness and equity, and to use that understanding to support more socially acceptable airspace modernisation. This paper summarises the conceptual basis, the qualitative and supplementary quantitative methods, the main findings from focus groups and Q methodology, and the resulting framework for assessing and communicating the relative risk of socially unacceptable outcomes.

FAIRNESS AND AIRSPACE CHANGE

The study drew on social justice research which distinguishes between distributional, procedural and informational/interactional fairness [5]. Distributional fairness concerns the perceived balance of costs and benefits. In an aircraft noise context, it relates to how overflight or noise burden is distributed across places and populations, and how any change compares with the existing situation. Procedural fairness concerns whether affected people are given a meaningful opportunity to influence the process. Informational fairness concerns the quality, honesty and comprehensibility of the explanations used to justify the process and the outcome.

These dimensions are highly relevant to airspace modernisation. A technically efficient design may still be judged unfair if it appears to place new or increased burdens on particular communities without adequate explanation, without a genuine choice between viable options, or without a credible route through which community views can influence the final decision. Conversely, even where a change cannot be made universally acceptable, a transparent and participatory process can reduce the risk that the outcome is seen as imposed or unjustified [5, 6].

A key premise of the FED2 study was therefore that social (un)acceptability is not determined by acoustic exposure alone. It is shaped by the lived experience of aircraft events, by expectations of place, by trust in decision-makers, and by whether the distributional trade-offs are made visible. The work also recognised that the question is rarely whether an outcome is

simply fair or unfair. Participants often expressed judgements along a spectrum: some options appeared less unfair, less disruptive or more understandable than others.

METHODS

The study combined qualitative community engagement with distributional noise assessment. It was developed through a staged process including an Expert Review Group, stakeholder focus groups, community fundamentals workshops, community focus groups, Q methodology and subsequent development and road-testing of a supplementary assessment framework. Table 1 summarises the main work stages which are set out in Figure 1.

Table 1: Overview of FED2 work stages

Stage	Purpose	Contribution to research
Expert Review Group	Independent review of planned tasks, progress and findings.	Helped test the logic and credibility of the approach.
Stakeholder focus groups	Explored concepts, barriers and practical issues with aviation and community stakeholders.	Informed realistic materials for community testing.
Community fundamentals workshops	Explored lived experience, concerns and possible future distribution concepts.	Refined the virtual airport materials and focus group design.
Community focus groups	Thirteen groups with over 130 participants from areas with different noise exposure.	Generated the core findings on distributional fairness and social (un)acceptability.
Q methodology	Explored common viewpoints and attitudes following the focus groups.	Supported interpretation of fairness, trust, growth and engagement themes.
Framework development	Combined N65, population and PEI concepts with qualitative findings.	Produced the proposed supplementary FED assessment and communication framework.

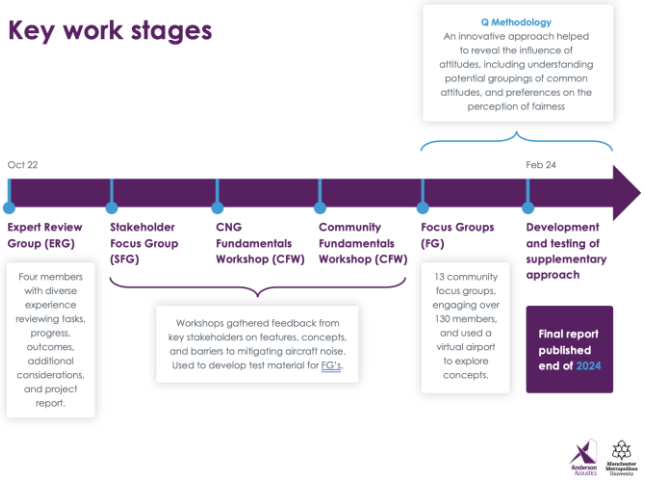

Figure 1: Key work stages

The key empirical method was the use of a virtual airport. Participants were introduced to a simplified airport, route system and baseline aircraft distribution before discussing four lateral distribution concepts. Removing direct reference to real villages and neighbourhoods was critical because it reduced location-based self-interest and enabled a more open discussion of the perceived fairness of different patterns of increases and decreases in aircraft noise events.

The baseline represented a conventional distribution of aircraft around an existing route centreline. The four concepts were: replication of the conventional route through more precise concentration; limited dispersal within the existing noise preferential route; wider dispersal with consequences extending beyond the existing corridor; and extensive sharing via a new route. For each concept, participants were shown graphical representations of the aircraft distribution and the resulting spatial pattern of N65 events, where N65 is the number of daytime events with a maximum noise level greater than 65 dB LAmax. Average noise level outputs were also considered, but the N65 outputs were generally more sensitive to the distributional changes under discussion.

Q methodology was used as a supplementary method to explore subjective viewpoints. It helped reveal groupings of common attitudes towards noise, fairness, compensation, respite, growth and the degree to which communities should influence decisions. The Q work was not intended to replace the focus group findings, but to add structure and nuance to the interpretation of the perspectives expressed.

FINDINGS

Perceptions of the four distribution concepts

The focus groups showed that participants could readily engage with the virtual airport materials and were able to compare the distributional implications of different concepts. The most consistent finding was that perceived fairness was dominated less by an abstract desire for equal sharing and more by the scale and location of change relative to the existing noise pattern.

The concentration concept, in which more precise navigation increased the burden around the route centreline, was widely regarded as unreasonable. Participants recognised that it might reduce exposure for people near the edges of the existing corridor, but the dominant concern was that those already most affected would receive an increased burden. This was commonly described as exacerbating an existing inequality and potentially pushing already exposed communities beyond tolerable limits.

The limited sharing concept was generally seen as more acceptable. Participants often felt that some spreading of aircraft movements within areas already experiencing overflight could reduce the burden on the most affected without creating a wholly new noise environment. However, this did not mean that all sharing was supported. Participants still asked who would experience the increase, how large the change would be, whether respite or scheduling would be provided, and whether future traffic growth would erode any benefit.

The wider sharing concept generated a more mixed response. Some participants saw it as a better compromise because it further diluted the burden on the centreline. Others considered that the wider the change, the more likely it would be noticed as a disruption to expectations, especially in quieter areas or places with particular environmental or land-use value. The discussion therefore suggested a potential tipping point at which the perceived benefit of sharing is outweighed by concern about the geographical extent of change.

The new route concept divided opinion most strongly. Some participants accepted a theoretical argument that a wider area could share the burden of aviation activity. However,

many considered it unfair to introduce aircraft noise to people who had not previously been overflown, particularly where people may have made housing or lifestyle choices based on existing conditions. This concern was heightened where new overflight might conflict with expectations of tranquility, rural setting, designated landscapes, schools, hospitals or other sensitive land uses.

The options are shown in Figure 2.

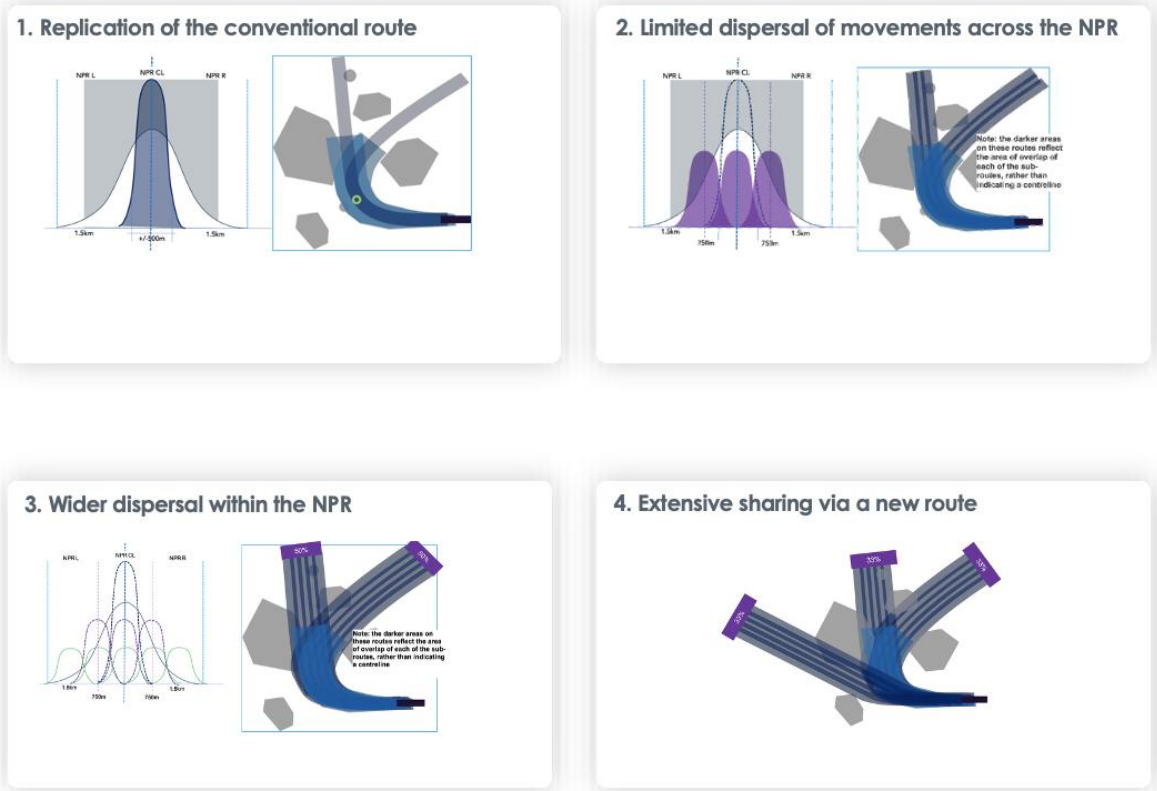

Figure 2: The four distribution concepts

Summary of distributional risk

Taken together, the findings suggest a spectrum of risk associated with different types of distributional change. The spectrum should not be treated as a universal rule, because local preference and context matter. However, for the Gatwick case study, minimal change with some limited sharing over already overflown areas appeared to carry lower risk than either increased concentration or extensive sharing into new areas.

Table 2: Distributional features linked to relative risk of social unacceptability

Distributional feature	Typical community concern	Relative risk implication
Increased concentration on existing centreline	Already burdened communities experience a further increase.	Higher risk, especially where health or quality-of-life concerns are already significant.
Limited sharing within already overflown areas	More people may experience some increase, but the most exposed may receive relief.	Lower risk where change is limited, explained and linked to reduced burden for the most affected.
Wider sharing beyond existing expectation	People at the edges or in quieter areas experience noticeable change.	Increasing risk as the scale and contrast of change increases.
New route or newly overflown areas	Noise is introduced into places where overflight was not expected.	Higher risk, moderated by local context, population, land use and mitigation.
Future traffic growth	Growth may erode the benefit of sharing or relief.	Risk increases if growth is not addressed transparently in engagement.

This is shown in Figure 3 below.

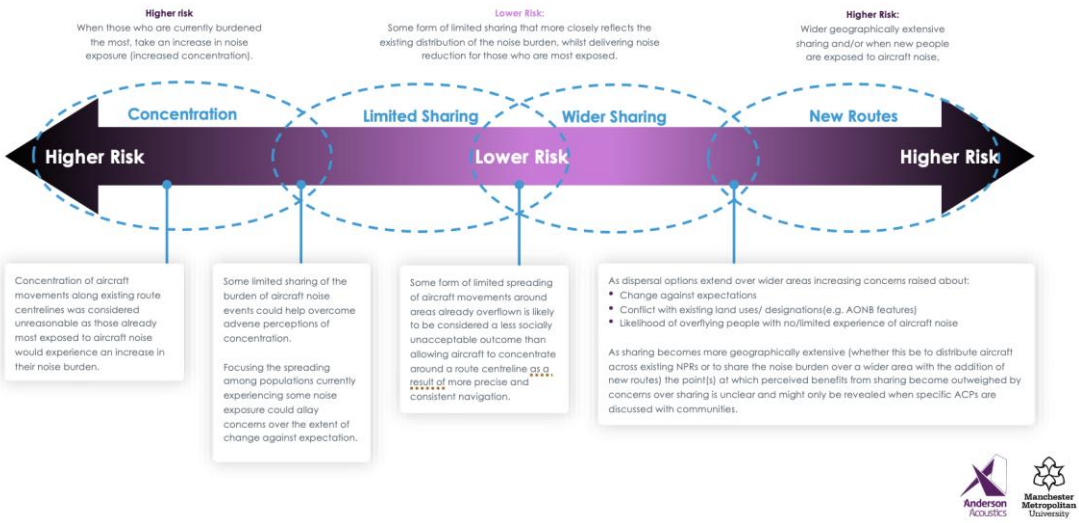

Figure 3: Spectrum of risk of social unacceptability associated with the perception of Distributional Fairness

These focus group findings were brought together into a hierarchy of risk to describe how different forms of change in the distribution of aircraft noise may increase or reduce the likelihood of socially unacceptable outcomes, see figure 4. The hierarchy reflects the finding that perceived fairness is strongly influenced by the extent of change from the existing noise environment, rather than by a simple preference for equal sharing. In the Gatwick case study, the lowest risk was associated with limited change to existing patterns, particularly where this could reduce the burden on those already most exposed. Risk increased where aircraft movements became more concentrated over communities already experiencing high levels of

overflight, or where wider sharing introduced noticeable noise into areas with little or no previous experience of aircraft noise. The hierarchy therefore provides a practical way of linking qualitative community judgements about fairness with measurable features of airspace design options, such as changes in N65 events, population exposure and Person Event Index.

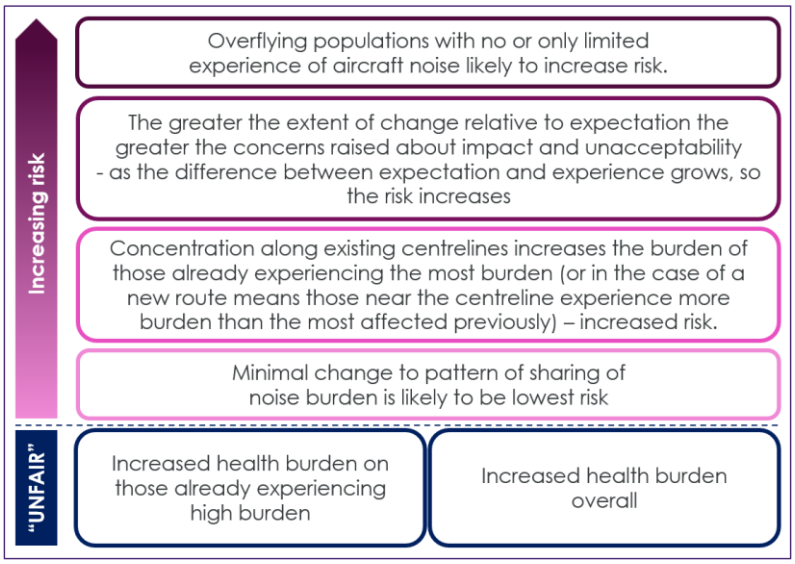

Figure 4: Hierarchy of risk

Procedural and informational fairness

Participants repeatedly linked fairness to the quality of engagement. Many comments reflected skepticism about whether consultation would genuinely affect decisions. This is important because CAP1616 requires engagement, but the perceived legitimacy of that engagement depends on whether communities believe that options are genuine, trade-offs are explained openly and preferences can influence outcomes.

The Q methodology reinforced this theme. Across viewpoints, there was support for engagement that is open, genuine, honest and transparent. Participants wanted to understand the number of flights, aircraft height, the distribution of events and the implications of future growth. Several viewpoints also raised compensation, respite or a realistic cap on flight numbers as part of a broader negotiation about acceptable outcomes.

These findings suggest that the assessment of airspace options should not be limited to identifying which option performs best against aggregate impact metrics. The process should also identify who experiences increased or decreased noise events, where those changes occur, how they compare with existing expectations, and how uncertainty and future growth are being addressed.

ROLE OF EVENT-BASED METRICS

A key methodological finding was the value of event-based metrics for public engagement. Participants found N65 illustrations helpful because they showed the spatial distribution of aircraft noise events and the change in that distribution. In contrast, equivalent changes in LAeq,T were often too small to be visually apparent for the lateral distribution concepts under discussion. This does not imply that average noise metrics are unimportant, but it shows that they may be insufficient on their own for explaining distributional change.

N65 is particularly useful because it is relatable to lived experience: people commonly describe aircraft noise in terms of events, frequency, interruptions and patterns over the day. Spatial change maps can show where events increase or decrease and can therefore make visible the distributional costs and benefits of each option. This supports informational fairness because it helps communities understand not only the sponsor's preferred outcome, but the trade-offs between viable alternatives.

The study also proposed linking event counts to population through the Person Events Index (PEI). In simple terms, PEI combines the number of events above a chosen threshold with the number of people exposed to those events [7]. This enables a fuller description of the population consequences of distributional change and can distinguish between options with similar aggregate exposure but different patterns of burden. In the FED2 framework, PEI is not proposed as a stand-alone decision rule. It is used to indicate relative distributional risk and support transparent discussion.

A SUPPLEMENTARY FED FRAMEWORK

The proposed framework is intended to complement, not replace, the policy-based assessment required in the airspace change process. It is designed to make distributional consequences more visible, improve engagement materials, and help sponsors identify options that may carry a higher risk of being perceived as unfair or socially unacceptable. The framework is therefore best understood as a structured support for assessment, refinement, shortlisting and communication.

The framework follows ten steps. The early steps present the spatial and narrative description of options and their N65 consequences. Middle steps relate N65 changes to population and derive PEI features. Later steps align these quantitative features with the qualitative hierarchy of relative risk and use the results to support engagement and risk moderation.

Table 3: Ten-step framework for assessing and communicating distributional consequences

Step	Action	Purpose
1	Present options spatially and narratively.	Explain the design intent and the route geography.
2	Present N65 and N65 change heat maps.	Show where event exposure increases and decreases.
3	Categorise N65 exposure into meaningful bands.	Translate event counts into understandable exposure categories.
4	Present N65 change categories spatially.	Show the extent and location of different degrees of change.
5	Relate N65 change to population distribution.	Identify communities and populations affected by each category.
6	Quantify populations exposed to N65 changes.	Summarise the aggregate population consequences of each option.
7	Calculate PEI and PEI differences.	Describe the event burden on people and how that burden changes.

8	Align N65 and PEI features with the risk hierarchy.	Translate quantitative outputs into relative fairness risk features.
9	Analyse aggregate changes for each proposal.	Compare options across population, N65 and PEI features.
10	Consider relative risk and mitigation.	Use the assessment to refine options and inform transparent engagement.

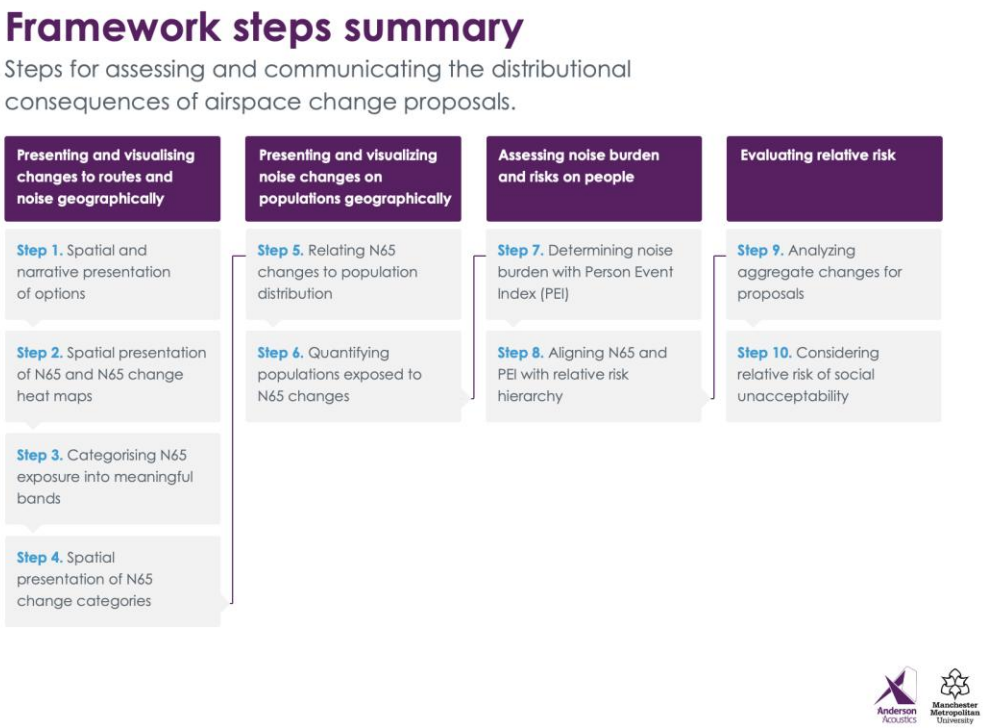

Figure 5: Framework steps

The framework is deliberately relative rather than absolute. A lower risk option is not risk-free, and a higher risk option should not automatically be rejected if it has strong safety, operational, environmental or policy justification. Instead, higher relative risk should trigger better explanation, stronger engagement, possible design refinement and a clearer mitigation strategy.

DISCUSSION

The FED2 findings have several implications for airspace change. First, distributional fairness should be considered explicitly alongside aggregate appraisal. Conventional policy metrics are essential for understanding total adverse effects, but they do not fully explain the social response to changes where events occur. Where an option produces an aggregate benefit by concentrating noise on a smaller group, or by moving noise into a newly overflown area, the distributional consequences need to be recognised and explained.

Second, community preference cannot be assumed to be the same at every airport. In this case study, participants generally preferred minimal change with limited sharing over already overflown areas. At another airport, different communities might favour concentration away

from centres of population, alternation, respite, or a different balance between sharing and protection. This means that early, neutral engagement is needed to understand local objectives before specific design options are presented as preferred.

Third, the language of fairness must be handled carefully. Equal distribution is not necessarily perceived as fair where it requires substantial change for communities with little previous experience of aircraft noise. Similarly, concentration is not necessarily accepted simply because it reduces the total number of people exposed. A fairer process is one in which the reasons for each trade-off are clear, the adverse consequences are not hidden, and affected communities can see how their input has shaped the final decision.

Fourth, the benefits of any distributional change need to be considered in the context of future traffic. Participants were concerned that limited sharing, respite or relief could be undermined if absolute aircraft numbers increase. This suggests that forecasts, growth assumptions and any proposed noise envelope or movement management approach should be presented in ways that are understandable and linked to lived experience metrics.

The study has limitations. The focus group and Q findings are qualitative and grounded in the Gatwick context. The proposed N65 bands and change categories should be tested and refined at other airports, and alternative thresholds such as N60 or N70 may be more appropriate in some settings or for night-time assessment. The framework also does not remove the need for professional judgement, policy compliance or operational feasibility. Its contribution is to make the distributional dimension of noise change more visible and more discussable.

CONCLUSIONS

The FED2 study shows that perceptions of fairness in airspace change are strongly shaped by the extent and location of change in aircraft noise events. Around Gatwick, participants did not generally interpret fairness as an equal sharing of noise. Rather, they were concerned with avoiding disproportionate increases for those already most exposed, limiting change against expectation, and treating newly overflown areas with particular care.

The work also shows that event-based metrics such as N65, particularly when combined with population through PEI, can support a more transparent account of distributional consequences than average noise metrics alone. Such metrics can help explain who experiences more or fewer events, where those changes occur and how options compare. This can improve informational fairness and provide a stronger basis for procedural fairness through meaningful engagement.

The proposed supplementary framework is not a decision-making tool and is not a challenge to existing policy. It is a practical means of supporting better assessment, clearer communication and more socially negotiated airspace outcomes. Its use should help airports and airspace change sponsors identify where the relative risk of perceived unfairness is greatest, refine options where possible, and engage communities with more honest and comprehensible information.

Further work should test the framework across different airport contexts, develop accessible communication tools, explore the use of Q methodology as a precursor to focus groups, and examine how event-based distributional evidence can be integrated into live CAP1616 engagement. The overall objective is to reduce the relative risk of socially unacceptable outcomes by combining noise reduction, fairer distributional reasoning and genuine community influence.

Acknowledgements

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Embedding a longitudinal quality of life study within an airport noise insulation scheme: delivery challenges and exposure methods

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ABSTRACT

Large airport noise insulation programmes can reduce indoor aircraft noise, but demonstrating wider benefits and maintaining community trust requires more than installation counts. We present a programme-level view of a longitudinal Quality of Life (QoL) study embedded within an ongoing insulation scheme, delivered through a partnership between an airport, an academic research team, and a service-integrator consultancy responsible for field delivery, resident engagement and quality assurance.

The study is designed to be light-touch for households while supporting repeated measurement. It combines complementary exposure approaches: (1) standardised facade sound insulation measurements using a controlled loudspeaker source to characterise repeatable building performance, and (2) aircraft-noise measurements to capture real-world operational variability. These data are linked to repeated resident questionnaires and scheme milestones, allowing change to be interpreted in the context of both building performance and the noise environment.

We focus on practical challenges that materially affect data quality and representativeness at scale: recruiting and retaining households over multiple years; appointment logistics in occupied homes; consistency of field teams, equipment and evidence standards; governance across multiple delivery partners; version control and traceability across large property cohorts; and transparent, fair communications as households move through phased roll-out. We outline controls used to manage these risks, including standard operating procedures, equipment calibration, metadata capture, audit trails, and a governance cadence for exceptions and resident complaints.

In our experience, longitudinal QoL evaluation embedded within routine scheme delivery is still uncommon in consultancy practice. The lessons presented are transferable to other large-scale community noise mitigation programmes.

INTRODUCTION

Noise insulation schemes are a widely used mitigation measure for aircraft noise. Increasingly, however, stakeholders expect evidence that these schemes deliver benefits beyond installation volumes, including improvements in annoyance, sleep disturbance, wellbeing and quality of life.

This paper addresses a practical question:

how can a longitudinal QoL evaluation be embedded within a live insulation programme in a way that minimises bias and preserves data integrity at scale?

Embedding evaluation into routine delivery introduces predictable operational pressures that can bias or undermine interpretation if they are not actively managed. Eligibility and scheduling are driven by scheme roll-out and installation timing; appointments must be delivered in occupied homes with variable access and conditions; field practice can drift across teams and time; multiple delivery partners have different priorities; and residents compare progress across areas during phased roll-out. We therefore present the service-integrator perspective, describing the embedded operating model, the main delivery failure modes that affect representativeness, consistency and traceability, and the controls and metrics used to keep the evaluation viable and defensible. A companion paper at this event, presented by the academic research team, reports preliminary quality of life and health findings from the pilot cohort; this paper focuses on the delivery system that produces those data.

DELIVERY MODEL AND EMBEDDED WORKFLOW

Delivery partnership and roles

The embedded study is delivered through a partnership between: (i) the airport (scheme owner and funder), (ii) an academic research team (study design, consent, questionnaires, analysis), and (iii) a service-integrator consultancy (field delivery, resident touchpoints tied to scheme delivery, and quality assurance across survey operations). The research participation is separate from scheme participation, and residents are informed that choosing not to participate does not affect scheme delivery.

Embedded Resident Pathway

A key feature of the model is that recruitment and eligibility are coupled to scheme milestones. The scheme is rolled out geographically over time and recruitment expands accordingly, with additional areas becoming eligible as the programme progresses. The practical consequence is that “the study sample” is not recruited in one block; it is built incrementally, in parallel with programme delivery.

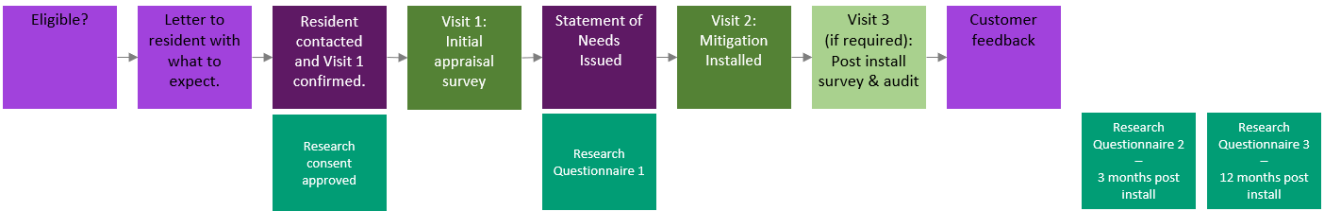

Figure 1. Embedded workflow from scheme delivery to linked longitudinal dataset (schematic).

METHODS

Questionnaires and participant burden

The questionnaire set is designed to be light-touch (approximately 10 minutes for baseline) to support participation in a live programme. Baseline content includes aircraft noise annoyance (overall/day/night), sleep disturbance, self-rated health and quality of life, wellbeing items (life satisfaction, worthwhile, happiness, anxiety), noise sensitivity, attitudes to aviation/airport, and demographic/dwelling context.

Consent, Linkage and Data Protection

Consent is obtained initially by the survey team and then followed up by the academic research team by either email or by telephone. The protocol sets out limits on contact attempts and clear separation of personal identifiers from research data via a study code. A DPIA and secure transfer processes are described, with study data managed to limit sharing of identifiable information between partners.

Exposure Methods

The exposure approach deliberately combines:

1. Repeatable building performance (controlled-source façade sound insulation)
2. Operational variability (aircraft-noise measurements under real-world conditions)

This combination is central to interpretation: changes in reported outcomes can be contextualised against both the achieved façade performance and the noise environment experienced during the relevant period.

Controlled-source façade sound insulation measurements (repeatable building performance)

Façade sound insulation testing is undertaken in general accordance with the global loudspeaker method in BS EN ISO 16283-3, supported by reverberation time measurement (ISO 3382-2) and evaluation of single-number quantities (ISO 717-1). Equipment and process controls include Class 1 instrumentation, pre- and post-survey calibration checks, defined loudspeaker positioning and measurement geometry, indoor and outdoor measurements, background noise checks, repeat rules when interrupted or unreliable, and structured metadata capture including photos and site notes.

A key delivery constraint is that façade testing is not always practicable (for example, upper-floor façades where incident level requirements cannot be achieved), which affects representativeness of measured building performance and must be tracked explicitly.

Aircraft-noise measurements (operational variability)

Ambient measurements are also undertaken at participating properties to capture noise exposure under real-world conditions inclusive of aircraft activity, with derived metrics including LAeq, LA90 and LAmax and a stated intention to avoid audio recordings for privacy.

Programme Delivery Challenges and Controls

This section summarises delivery challenges that materially affect data quality and representativeness at scale, and the controls used to manage them. The intention is to describe what must be true operationally for an embedded longitudinal evaluation to remain interpretable.

1. **Recruitment during live programme delivery**: Recruitment is coupled to scheme touchpoints and expands by zone as eligibility opens, which can create uneven opportunities and selection bias if participation varies across areas or time. Controls include clear messaging that participation does not affect scheme delivery, limited contact attempts, and a low-burden questionnaire. Evidence to track includes funnel metrics by zone and over time, from consent-to-contact through consent and baseline completion.

2. **Retention across multiple waves and real-life changes**: Follow-up is vulnerable to attrition due to time pressures and life changes, as well as scheme-related dissatisfaction or self-led modifications, which can bias estimated change if drop-out is non-random. Controls include keeping the survey light-touch, using reminders, and rapid triage of issues that risk disengagement. Evidence to track includes follow-up completion among eligible participants and recorded withdrawal reasons.

3. **Appointment logistics in occupied homes**: Fieldwork in lived-in homes brings restricted access, furniture constraints, interruptions, narrow time windows, and cancellations, which can increase measurement issues, reduce comparability, and create missing exposure data. Controls include SOPs (including repeat rules), structured site notes, and metadata capture to document deviations. Evidence to track includes rescheduling rates, incomplete visits, repeats due to interruption, and deviation counts.

4. **Consistency of field teams, equipment and evidence standards**: High-throughput delivery increases the risk of process drift across staff and time, which can pose as intervention effects or obscure true change. Controls include training and competency expectations, consistent equipment configuration and calibration discipline, standardised geometry and acceptance criteria, and mandatory photo/metadata evidence. Evidence to track includes calibration compliance, metadata completeness, repeatability checks, and QA audit findings.

5. **Governance across multiple delivery partners**: Embedded programmes involve partners with different priorities, and exceptions (unusual properties, complaints, atypical conditions) require consistent decisions; without this, exception handling becomes inconsistent and undermines trust and data integrity. Controls include defined escalation routes, documented exception decisions, and a regular governance cadence to review complaints, exceptions and protocol issues.

6. V**ersion control, traceability and audit trails at scale**: Large phased cohorts create risks of mislinking questionnaires to measurements, misaligning measurements to milestones, and using inconsistent field document versions, which can invalidate longitudinal comparisons. Controls include unique study codes and scheme identifiers, structured naming and data packaging, and explicit metadata capture. Evidence to track includes linkage query rates, missing identifiers, and audit sampling of record completeness.

7. **Data volume and data orchestration**: Multiple data streams per dwelling (façade datasets, metadata/photos/site notes, equipment and calibration evidence, aircraft/ambient metrics) must be coordinated with installation milestones to trigger repeat post-install work at the correct timepoints; this increases the risk of mislinking, version drift, missed follow-ups and loss of provenance. Controls include a standardised per-visit data package with completeness checks, disciplined use of identifiers and crosswalks with milestone reconciliation, controlled template/protocol updates, and QA sampling with an auditable trail for edits and exceptions. Evidence to track includes minimum-dataset completeness, linkage error/query rates, follow-up scheduling timeliness and missed follow-ups, and version compliance.

8. **Transparent and fair communications during phased roll-out**: Residents compare progress across areas and can perceive unfairness, which affects participation, retention and cooperation during visits, and ultimately the legitimacy of findings. Controls include clear, consistent messaging on eligibility and phasing, transparent complaint handling, and consistent expectations on visit duration and disruption. Evidence to track can include complaint rates and themes by area and time, and any corresponding changes in conversion or retention.

Table 1. Delivery challenges, risks to data quality, and operational controls (summary)

Challenge	Risk	Controls	Evidence / metric
1. Recruitment in live delivery	Selection bias; uneven recruitment	Clear "no impact on scheme"; timed invitations; capped contact attempts; low-burden survey	Funnel by zone: contact-consent → consent → baseline; consent rate by zone
2. Retention over waves	Attrition bias; missingness	Short follow-ups; reminders; triage dissatisfaction; log withdrawal reasons	3m/12m completion among eligible; all-waves completion; withdrawal reasons
3. Occupied-home logistics	Missing/inconsistent exposure; deviations	Confirmed appointments; resident briefing; repeat rules; structured notes + photo/metadata checklist	No-shows/cancels; re-visits; % interrupted repeats; metadata completeness
4. Team /equipment consistency	Drift; non-comparability	SOPs + training; fixed configs; pre/post calibration; acceptance criteria; QA spot checks	Calibration compliance; QA findings; outlier rate; repeatability subset
5. Multi-partner governance	Inconsistent exceptions; complaint drag	RACI; exception/complaint cadence; documented decisions; protocol change control	Time-to-close exceptions; complaint outcomes; change log; re-test rate
6. Traceability /version control	Mislinking; wrong timepoints	Study code + property ID; naming conventions; secure transfer; edit audit trail; import cross-checks	ID completeness; linkage error rate; QA mismatch rate; audit pass rate
7. Data volume and multi-stream orchestration	Linkage errors; inconsistent versions/templates; delayed follow-up eligibility tracking; loss of provenance	Structured naming/packaging; protocol/template change control; audit trail for exceptions; defined data handover points	Linkage query/error rate; % records with complete required artefacts (metrics + metadata + calibration); time-to-resolve data queries; protocol/template version log
8. Phased-rollout comms	Trust loss → bias; complaints	Clear phasing comms; set disruption expectations; scripts; feedback loop	Complaint rate by zone/time; feedback themes; drop-out after issues; conversion shifts

CURRENT PROGRAMME METRICS

The embedded model creates measurable attrition points. As of 28 February 2026:

- Consent-to-contact: 686
- Consented to participate: 225 (33%)
- Baseline completed: 217 (96% of consented)
- 3-month completed: 56 of 88 eligible (64%)
- 12-month completed: 51 of 83 eligible
- All three waves completed: 44 of 83 eligible (53%)

Most withdrawals occurred prior to baseline completion; post-baseline withdrawals were limited and included both practical and scheme-related reasons.

These metrics support two practical conclusions relevant to embedded delivery: (i) baseline completion can be high once consent is secured, but (ii) retaining participants through follow-up requires targeted controls and ongoing attention to resident experience and scheme coordination.

DISCUSSION

This paper argues that the main risk in embedded longitudinal QoL evaluation is not the inability to design a study, but the difficulty of maintaining a stable, auditable delivery system under real-world constraints. The combination of a controlled-source façade test and ambient aircraft-noise measurements is intended to separate two sources of variation that matter for interpretation: the achieved performance of the dwelling envelope (repeatable) and the operational noise environment (variable). The challenge is ensuring both datasets are collected consistently and linked reliably to scheme milestones and questionnaires.

A central transferable lesson is the need to treat the embedded study as an operational product with explicit quality controls: standardised procedures, evidence standards, traceability by design, and governance mechanisms for exceptions. Without these, longitudinal conclusions are vulnerable to untracked deviations, selection effects and inconsistent handling of complaints or constraints.

LIMITATIONS

The sample is embedded in scheme eligibility and phased rollout and is therefore an opportunity sample rather than a population-representative sample. Some dwelling types or façade contexts may be excluded from controlled-source testing due to practical constraints (e.g. upper floors), which affects representativeness of measured façade performance. Follow-up eligibility depends on installation timing, which can change the composition of the follow-up cohorts.

CONCLUSIONS

Embedding a longitudinal QoL evaluation within a large airport insulation scheme is feasible at scale, but it succeeds or fails on delivery. Namely, recruitment and retention, appointment logistics, consistency of field practice, governance for exceptions, traceability, and transparent communications during phased roll-out.

Exposure methods can be robust and repeatable, but only if the operational system that implements them remains stable and auditable. The delivery lessons described are transferable to other large-scale community noise mitigation programmes seeking credible evidence of benefits beyond installation counts.

ACKNOWLEDGEMENTS

This work was delivered as an embedded Quality of Life evaluation within the Heathrow noise insulation scheme through a partnership between Heathrow Airport, City St George's, University of London (academic research team led by Professor Charlotte Clark), and Anderson Acoustics Ltd (service integrator and field delivery partner). We thank colleagues at Heathrow for programme sponsorship and support, the City St George's research team for study design and delivery of the questionnaire programme, and all delivery partners involved in coordinating access and installations. Above all, we are grateful to the residents who gave their time to participate in questionnaires and accommodate measurements in their homes.

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Deriving the number of people highly annoyed from standardised scales – a case for better harmonisation

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ABSTRACT

Quantifying the proportion of people who are highly annoyed by noise is central to communicating the societal impact of noise. Annoyance, as assessed in socio-acoustic surveys, is a multidimensional construct incorporating repeated disturbance, emotional and attitudinal reactions, and cognitive appraisal. It is recognised both as a health outcome in its own right and as a mediator linking environmental noise to more serious physical and mental health conditions. Consequently, the percentage of the population that is highly annoyed (%HA) at a given sound level has been a key metric informing policy, regulation, and guidelines for more than six decades. A major step toward harmonisation was the publication of ISO/TS 15666 in 2003, grounded in earlier ICBEN work, which provided a standardised approach for assessing noise annoyance.

The most recent version of the standard permits two response scales (a 5-point verbal and an 11-point numeric scale) and three alternative computations of %HA. This paper briefly reviews the historical development of these methods and presents case studies demonstrating how these different approaches can yield substantially different %HA estimates. We argue that such variability is problematic when %HA is used in policy and decision-making contexts, such as the setting of noise thresholds or the monetisation of health impacts.

We conclude by proposing a pathway towards a harmonised definition of %HA ahead of the next revision of ISO/TS 15666. Our recommendations draw on original ICBEN guidance, recent comparative analyses of %HA algorithms, and recent work deriving disability weights for moderate and high noise annoyance.

INTRODUCTION

Noise annoyance and sleep disturbance are arguably the most recognised and accepted effects or impacts of long-term noise exposure, backed by many decades of socio-acoustic studies [1]. Whilst recent quantitative health risk assessments include an increasing range of

physiological and mental health outcomes attributable to noise [2], noise annoyance generally ranks in the top three health outcomes in terms of number of people affected and years lived with disability. Furthermore, a growing body of evidence is pointing to noise annoyance's important role in moderating and/or mediating the relationship between noise and mental health [3-6]. Beyond transport noise, self-reported health outcomes such as annoyance may be the only health effects quantifiable at a population level for noise sources that are difficult to characterise by an averaged sound metric – e.g. neighbour, commercial, and/or entertainment.

Noise annoyance as observed in socio-acoustic surveys is a retrospective judgment, comprising past experiences with a noise source over a certain time period. This multi-faceted response is seen by many researchers as a stress-reaction involving an environmental threat and individual physiological, emotional, cognitive, and behavioural responses which can partly be remembered and be integrated into a long-term annoyance judgement [7]. In this article we only refer to studies investigating long-term exposure in a real world setting, for example residents living in areas exposed to transport noise.

Schultz [8] was one of the first to try to translate different noise ratings in annoyance studies to develop a uniform assessment of the percentage of the survey population who were "highly annoyed". Schultz made several arguments in favour of focusing on the "highly annoyed" (HA) part of the population [8]:

- When people are highly annoyed by noise, the effect of non-acoustic factors is reduced and the correlation between noise exposure and subjective reactions is high.
- We are dealing with people who have attended to the outdoor noise, because they exhibit a definite and conscious response to it; and therefore there is a better chance of discovering a meaningful relation between outdoor noise exposure and annoyance.
- It is better understood by politicians and policy makers.
- Median annoyance is "*diluted and is anchored by the responses of the continual complainers and the noise imperturbables*". Shultz argued that median annoyance does not adequately describe that part of the population whose expressed annoyance changes with noise exposure, and hence it is too sluggish and insensitive for regulatory purposes.

Schultz proposed a HA cutoff at around 72% on a hypothetical 0-100 scale, arguing that:

"if the data are presented in only, say, seven steps along the annoyance scale, then the options as to who should be counted as highly annoyed are considerably restricted. If one counts only the top step, or 14.3% of the scale, one surely risks missing some of the highly annoyed population. Counting the top two categories out of seven (or 29% of the annoyance scale) seems more reasonable; but counting the top three categories (43%) includes almost the entire top half of the scale, and would surely exaggerate the count of people "highly annoyed.""

Two Swiss surveys were also referenced, where people were reported as highly annoyed if they responded in the top three out of eleven categories (top 27% of annoyance scale), which was deemed by Shultz as "*a reasonable definition of high annoyance*". However, for the surveys using verbal annoyance scales where respondents could state directly their degree of annoyance, "*those people were counted as highly annoyed who said they were highly annoyed*". Therefore Schultz included the category "very" in his definition of HA.

Schultz's approach was critiqued in several subsequent publications. For example, Fields [9] argued there was a lack of agreement between some of Shultz's choices and the judgements of the experts conducting some of the original studies. An example was quoted where an

elaborate analysis for a Heathrow survey concluded that the top 3.5 points of a seven point scale appeared to be a reasonable interpretation of serious annoyance. Fields [9] noted that:

"*there is no true objective definition of "high annoyance". All that can be scientifically determined is whether scales measure the same degree of annoyance. That statement can only be determined on an empirical basis by comparing the answers of the same population to alternative annoyance measures."*

In 1998 Miedema & Vos [10] published a new meta-analysis of annoyance studies that aimed to avoid "errors and inaccuracies" in previous syntheses published by others. To address criticisms of the Schultz's approach for combining different %HA methodologies, they proposed a purely mathematical approach of aligning scores with different number of items, making two assumptions to simplify the analysis:

- Equal intervals: each category from a set of response alternatives occupies an equal portion of the annoyance continuum;
- Equal extremes: the extreme (lower and upper) category boundaries from different sets of annoyance response alternatives coincide.

However, they kept the cutoff proposed by Schultz of approximately 72% to represent "highly annoyed", noting that "*an advantage of using a cutoff at 72 over lower cutoff values is that percentages obtained with the cutoff at 72 are less affected by differences between studies in the usage of a filter question*". They also stated that for "*five studies (AUS-014, AUS-093, FRA-019, JAP-065, and USA-250) with a cutoff point very different from 72 (60, 50, 50, 50, and between 50 and 60, respectively) we could not derive percentages with a cutoff point closer to 72. Because 72 is by convention the cutoff to be used for determining %HA, we excluded these five studies*" [10]. A subsequent publication [11] used an "improved model" that gave confidence intervals. The curves proposed by Miedema et al. were implemented in WHO methodologies [12] for quantifying the burden of disease of noise, and became the *de facto* standard of quantifying annoyance in many countries for the following two decades. As of May 2026, these curves are still referenced in the UK's transport analysis guidance [13].

In order to simplify future inter-survey comparisons, in 1993 the ICBEN (International Commission on Biological Effects of Noise) Community Response to Noise team commenced seven years of research to formalise a standardized methodology for assessing noise annoyance [14]. This included the publication of reporting guidelines for socio-acoustic surveys in 1997 [15] and recommendations for standard noise reaction questions in 2001 [16]. Many of their recommendations were published in 2003 as Technical Specification ISO/TS 15666 by the International Standards Organization (ISO). The ICBEN team recommended two noise reaction questions: a 5-point verbal scale question and an 11-point numeric scale question. They also recommended that high annoyance is defined by the "very" and "extremely" points on the verbal scale (equivalent to a 60% cutoff on a 0 – 100 scale, assuming equal intervals). No recommendation was made for the 11-point numeric scale because in this case "*the respondents' answers do not provide a clear basis for a division*". However further research comparing the two scales was recommended.

CURRENT PRACTICES FOR QUANTIFYING %HA

In the WHO-commissioned systematic review and meta-analysis on noise annoyance [7], most eligible studies published between 2000 – 2014 used the 72% cutoff for determining %HA, with only a minority of studies using the 60% cutoff. However, a subsequent update by Fenech et al. [17] found that approximately the same number of studies on road and railway noise annoyance published between 2014 and 2022 used the 11-point scale with a 72% cutoff and the 5-point scale with a 60% cutoff. A further three studies used the 5-point scale but with a weighted approach as an attempt to approximate a 72% cutoff.

Table 1: Number of noise annoyance surveys published between 2000 - 2014 included in systematic review and meta-analysis by Guski et al. [7], split by type of annoyance scales. Adapted from Brink et al. [18].

Noise Source	11-point only	5-point only	Both 11-point and 5-point	Other scales
Road, railway, aircraft, wind turbines, combined	19	9	20	9

Table 2: Number of noise annoyance studies published between 2014 - 2022 included in review and meta-analysis by Fenech et al. [17], categorised according to their methodology for reporting %HA.

Noise source	11-point scale, 72% cut-off (HA_N)	5-point scale, 60% cut-off (HA_V)	5-point scale, 72% cut-off (HA_{VW})	Other scales
Road, railway	6	7[a]	3	1[b]
[a] 1 study used a modified preamble to refer to annoyance indoors with windows closed [b] 1 study 4-point verbal with 75% cutoff;				

ISO/TS 15666:2003 did not prescribe how the 5-point verbal scale question and the 11-point numeric scale question should be scored, allowing for flexibility in how countries may wish to score annoyance. However, the lack of standardised scoring can impede cross-study and cross-country comparisons. ISO/TS 15666 was updated in 2021 [19] by an international working group (ISO/TC 43/SC 1/WG 62). The update was accompanied by a paper by Clark et al. [14] that provided a comprehensive overview of the rationale for the changes in the updated standard. One of the key changes in the 2021 update was the inclusion of three recommended methods for quantifying %HA:

- Numerical values 8, 9, and 10 for the 11-point numerical scale (HA_N) – citing Schultz [8].
- The top two verbal response categories for the 5-point verbal scale (i.e., very and extremely) (HA_V) – citing the ICBEN recommendations [16] and Schultz [8]
- The top two verbal response categories on the 5-point verbal scale (i.e., very and extremely) with 'extremely' counted in full, and 'very' weighted by a factor 0.4 (HA_{vw}) - citing [20] and [21]. The standard claims that this weighted approach *"creates a greater mathematical similarity between this scale and studies that have reported high annoyance as the top 28 % on the 11-point numerical scale*".

HA_{vw} was proposed for use where %HA was to be compared across studies using the two different question formats, and was not intended to replace the use of HA_V in individual surveys where it had been measured. It was primarily added to support the development of international databases for annoyance.

The standard references two studies [20, 21] to support the HA_{VW} proposal. Brink et al. [20] showed that HA_{VW} "*puts the %HA considerably below the corresponding value on the 11-point scale in almost all but the lowest L_{dn} categories*" (see Figure 1). In [21], Wothge et al. looked at %HA using the HA_v and HA_{vw} methodologies but did not make comparisons with HA_N.

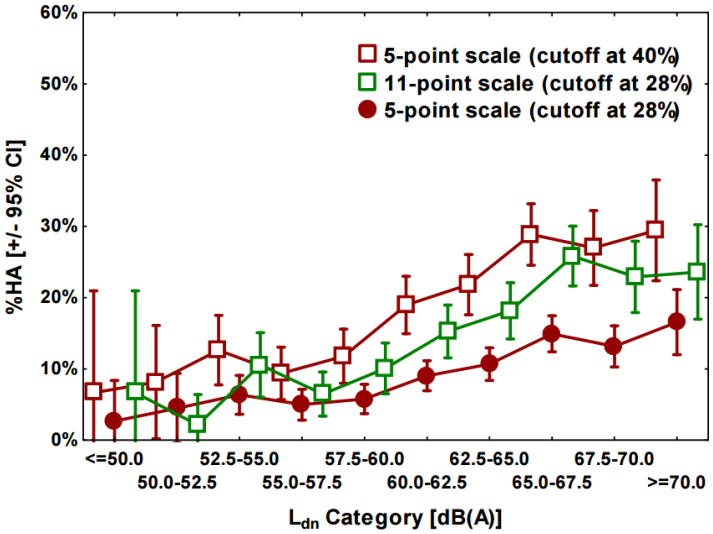

Figure 1: Comparison of exposure response relationships for percentage highly annoyed using the three methods in ISO/TS 15666:2021. Data from a socio acoustic survey of a stratified random sample of road traffic noise-exposed inhabitants in Switzerland. Figure reproduced from Brink et al. (2016) [20].

CURRENT CHALLENGES

In their paper explaining the rationale for the 2021 changes to ISO/TS 15666, Clark et al. [14] referenced a third study [22] to support the inclusion of the weighted version. In this study, Gjestland et al. present %HA calculated according to HA_N and HA_{VW}. The results show clear differences in the %HA calculated using the two methodologies (c.f. Tables II – IX in [22]).

Clark et al. [14] acknowledge the conclusion in [20] that weighting the 5-point verbal scale question as an attempt to align cut-off points on the two scales "*does not automatically produce congruent exposure-annoyance relationships*". They also acknowledge concerns that making the 5-point verbal scale question cut-off similar to the 11-point numeric scale question omits a large proportion of those who are annoyed from the analysis. An additional cited study, Michaud et al. [23], showed that a cut-off based on the top *four* responses on the 11-point scale (cut-off of 64%) was more strongly correlated with the top two verbal response categories of "Very" and "Extremely". Michaud et al. [23] therefore argued that the conventional cut-off for the 11-point numeric scale question could be underestimating %HA.

Brink et al. [18] argue that the conversion of %HA derived from the verbal 5-point annoyance scale into %HA according to the 11-point numerical scale is less straightforward than implied in ISO/TS 15666:2021. On the numerical scale, "high annoyance" is defined by scores from 8 to 10 (HA_N), corresponding to a cutoff at 72.73 on a 0–100 scale. This cutoff falls within the "very annoyed" response category of the verbal scale, which ranges from 60 to 80 on the 0-100 scale. Assuming a uniform distribution of annoyance intensity within this category, 36% of "very annoyed" responses would exceed the HA_N cutoff, while 64% would remain below it. This theoretical assumption serves as the basis for weighting "very annoyed" responses to 0.36 (or 0.40 when using a rounded cutoff of 72).

However, Brink et al. [18] report that empirical findings from studies applying both annoyance scales do not consistently support this assumption. In most datasets re-analysed in their study, the proportion of respondents classified as HA_N among those selecting "very annoyed" exceeded 36%, with an average of approximately 50%. The authors further demonstrate that different assumptions regarding this proportion result in substantially different exposure–response relationships for %HA, indicating that the choice of weighting factor has a considerable influence on model outcomes. Instead of directly weighting "very annoyed"

responses, they propose an exposure–response modelling approach based on simulation, in which all “extremely annoyed” respondents are classified as highly annoyed, and a percentage of “very annoyed” respondents are randomly assigned to the HA category across several hundred iterations. Supplementary R code implementing this procedure was provided in the publication. However this approach has some limitations. Researchers need to be clear on why they wish to compare the 5-point scale with the 11-point scale, and to understand the statistical limitations on data once the simulation has been run. It will allow the estimation of %HA that may be more closely aligned with HA_N (but at the same time underestimating HA_V). We argue that this approach has limited use in further analyses predicting annoyance, or to understand the influence of non-acoustic factors.

One of the primary purposes of deriving exposure response relationships (ERR) for %HA is to obtain quantitative estimates of the noise impact on exposed populations to influence policy and decision making. Williams et al. [24] compared the impact of different exposure response relationships (ERRs) for aviation noise annoyance on the predicted burden of disease at a national level (England). The ERRs were derived from the Survey of Noise Attitudes (SoNA) 2014 dataset [25]. The dataset contains responses from a total of 1,999 respondents aged 18 years and over and living in proximity to nine of the largest airports in England, who completed face-to-face interviews between October 2014 – February 2015. SoNA 2014 included three questions about aviation noise annoyance that can be used to derive an ERR for highly annoyed: A9a, CAN1i (both using a 5-point scale) and CAN 34 (using an 11-point scale). A9a and CAN1i were analysed to give HA_V (60% cut-off) and HA_{VW} (72% cut-off), giving five separate ERRs in total. The predicted Disability Adjusted Life Years (DALYs) for the assessment year varied between 2,800 and 5,350, based on the same aviation noise exposure dataset (see Figure 2). Whilst some of the differences may be due to question placement in the survey (A9a was towards the beginning; CAN 34 was towards the end of the questionnaire), the three methods proposed in ISO/TS 15666:2021 give very different results. This leads to confusion amongst policy and decision makers, industry and community groups affected by noise.

	Main ERR *Guski et al. 2017* ≥50 dB L_{den}	**Sensitivity ERR** *SoNA A9a* ≥50 dB $L_{Aeq,16hr}$	**Sensitivity ERR** *SoNA CAN1i* ≥50 dB $L_{Aeq,16hr}$	**Sensitivity ERR** *SoNA CAN34* ≥50 dB $L_{Aeq,16hr}$
ERR HA cut-off	n/a	60%	60%	-
% of population	1.2	0.63	0.58	-
Number of people	524,321	267,433	245,896	-
Total DALYs/yr	10,486	5,349	4,918	-
DALYs per 100,000 people/yr	25	13	12	-
ERR HA cut-off		72%	72%	72%
% of population	-	0.42	0.39	0.33
Number of people	-	180,491	168,083	140,057
Total DALYs/yr	-	3,610	3,362	2,801
DALYs per 100,000 people/yr	-	8	8	7

Figure 2: Sensitivity analysis showing the effect of exposure response functions generated according to the three methods in ISO/TS 15666:2021 on the calculated burden of disease from aircraft noise in England. Reproduced from Williams et al. [24].

A PATHWAY TOWARDS BETTER HARMONISATION

ISO/TS 15666:2021 is due for its next systematic review in 2027, and this is a timely opportunity to review and reflect on the current evidence, and narrow down the options of calculating %HA to two or, ideally a single agreed way.

Is HA_{VW} still defensible?

HA_{VW} was proposed to approximate a 72% cutoff when using the 5-point verbal scale to enable comparisons with HA calculated using the 11-point scale, if needed. By definition, HA_{VW} always gives lower estimates of people highly annoyed than HA_V. An important question to explore is why Schultz's proposed 72% cut-off was accepted by some as the "true" or reference cut-off, whilst ICBEN's recommendation that the "very" and "extremely" scores represent "highly annoyed" was given less prominence. The ICBEN recommendation [16] was informed by a research project that was used to choose the labels for the answers to the 5-point verbal scale and for the endpoints of the 0-10 numeric scale. The project captured data from 1754 subjects at over 25 sites in 12 countries in nine languages. One aspect of this study was a semantic intensity score analysis, where subjects indicated the intensity associated with several descriptive words on a 10-cm line that extended from "No/lowest degree of annoyance" to "Highest degree of annoyance". Some of the descriptive words and their resulting intensity (0 – 100) scores were: "considerably" (62), "substantially" (64), "importantly" (65), "significantly" (67), "very" (76), "highly" (79), "strongly" (80), "severely" (91), "tremendously" (92), and "extremely" (95). "Very" was the closest of the five chosen scale words to "highly". According to the ICBEN team, using two points ("very" and "extremely"), rather than one point to define "high" annoyance reduces the effect of any tendencies to avoid or select the endpoints of scales. The ICBEN team did note that their proposed cutoff, equivalent to 60%, was lower than the 72% cutting point proposed by Schultz [8]. However, the team emphasised that the 60% division encompasses words such as "considerably", "substantially", and "importantly"; all of which indicate levels of annoyance that are not regarded as being trivial or moderate.

The ICBEN recommendations also stipulate that the words on the verbal scale should not be identified by numbers because [16] "*numbers might distort respondents' judgments away from the words' intrinsic intensity scores and thus also away from the intensity scores that are assumed to apply by the report readers who base their interpretation on only the words*".

To understand in more detail how survey respondents respond to the 11-point and five-point scales within the same survey, Brink et al. [20] plotted the frequency distributions of the chosen responses on one scale for each scale point on the respective other scale. Figure 3 reproduces the distributions equivalent to the "very" on the 5-point scale, and scores "7" and "8" on the 11-point scale. Figure 4 shows the equivalent plots using the UK SoNA 2014 dataset introduced earlier.

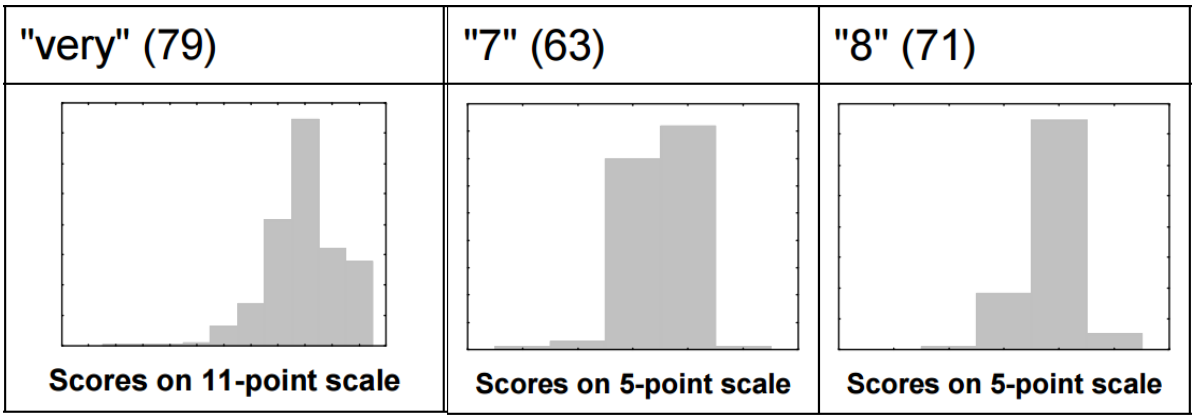

Figure 3: Distribution of annoyance score values within a stratified random sample of road traffic noise-exposed inhabitants in Switzerland. Left: Distribution of 11-point scores for participants that chose the "very" on 5-point scale. Middle and right: Distribution of 5-point scores for participants that chose 7 or 8 on the 11-point scale. Reproduced from Brink et al. [20].

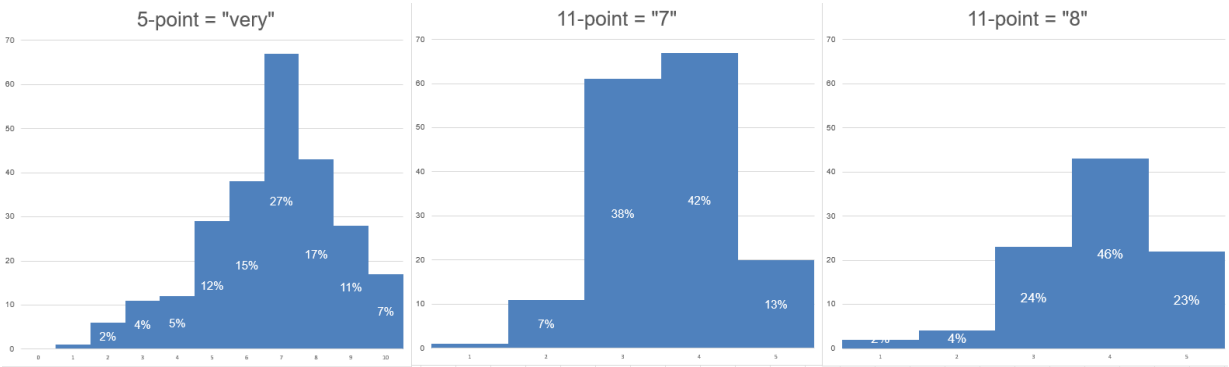

Figure 4 Distribution of annoyance score values in a random sample of aircraft noise-exposed inhabitants in the UK (SoNA 2014). Left: Distribution of 11-point scores for participants that chose the "very" on 5-point scale. Middle and right: Distribution of 5-point scores for participants that chose 7 or 8 on the 11-point scale. Figures generated from data from [25], based on questions A9a and CAN34.

These datasets show that:

- Participants that are "very" annoyed by noise are not fully captured by the top 3 scores on the 11-point scale. For the UK dataset, the most frequent score for those reporting "very" annoyed was 7 on the 11-point scale.
- In both studies, approximately half of the respondents that chose score "7" on the 11-point scale report they are "very" or "extremely" annoyed by noise on the 5-point scale.

Therefore, if we accept the ICBEN definition of "highly annoyed", the current data suggests that choosing the top three scores on the 11-point scale underestimates the number of people who consider themselves "very" or "extremely" annoyed.

Choosing between verbal and numeric scales

In the informative Annex of ISO/TS 15666:2021, the standard recommends that both annoyance questions (scales) are used to increase the reliability of a measurement, enhance comparability and to advance "*the body of evidence pertaining to the interchangeability between the two questions and by extension the optimal derivation of highly annoyed*". In the same Annex, the standard notes that each scale has strengths and weaknesses, but states: "*If having to choose between the verbal and/or the numerical scale, the recommendation is to use the 11-point numerical scale, as it affords the greatest options for statistical testing and cross-study comparisons.*" On the latter point, the Annex notes that one of the disadvantages of the 5-point scale is that "*within cultures the meaning of language can change over time, which could influence the respondents' perception of the verbal scale …. Although efforts have been made to stabilize the response categories across cultures …, the terminology used in the response categories can be culturally bound and this can add uncertainty to cross-study comparisons.*" However, this somewhat ignores the fact that the numeric score is still preceded by a (lengthy) verbal Introduction and Question that could be interpreted differently depending on culture and language.

If we agree that the primary focus of asking the annoyance question is to extract the %HA, then the method that is best at capturing the outcome should take precedence over methods that give the "greatest options for statistical testing". Further, we argue that the need to be able to compare responses from surveys using the 5-point scale to those from surveys using the 11-point scale is not justified. As more surveys are undertaken and international databases established, the number of surveys is constantly increasing, thereby enabling more reliable comparisons using the same question. The dominance of the 11-point scale is not as strong as believed several years ago. However, even if we try to compare 'like' with 'like' the issues of the different cut-offs, and the inadequacy of the weighted approach still remain.

Back to Basics – refocusing on the outcome

Throughout the nearly 50-year history of trying to synthesise annoyance responses, there have been some rather complex mathematical and statistical efforts to try to align different scores [11, 18]. We question whether this is necessary, when the raw data are essentially simple responses to questionnaires. When we as noise and health researchers and practitioners are speaking about annoyance with non-specialists, whether that is politicians, policy officials and community groups affected by noise, the emphasis is always on the semantics of the wording "highly annoyed". We accept there may be a degree of variation in how the word "highly" is interpreted by these different stakeholders.

Another important argument is how the number of people highly annoyed is translated into life years lost in disability (DALYs) in health risk assessment. A key component of the methodology is the disability weight assigned to the outcome "high annoyance". The disability weights study [26] underpinning the new values proposed in the WHO 2024 report [27] presented the following description of "highly annoyed" to study participants:

Annoyance: severe "*is highly annoyed because of loud noises in the surroundings*".

So once again the focus was on the semantics of the phrase "highly annoyed", as opposed to a certain cutoff on a numeric scale. From an outcome perspective, it is hard to argue against the simplicity and face validity of the 5-point scale.

Time for one question

The provision of two questions to assess annoyance put forward by ICBEN in 2001 and TS/ISO15666 in 2003 was instrumental to improve consistency in how we measure this highly prevalent health impact associated with noise. However, it is now time to consider whether we should go a step further. There are few, if any, health outcomes that are defined using two similarly worded questions with different response scales. Yes, multiple indicators from different sources can be used to indicate a health condition in epidemiological studies, such as the use of blood pressure measurement, medication use, and self-report of diagnosis for hypertension, but this is not what is happening for annoyance. The field has been unable to resolve over many decades which question to use. We argue that there ought to be one question in the standard, and to achieve this, sacrifices will have to be made.

Nations and researchers tend to favour one of the questions. This is often driven by precedent and historical use of one of the questions to track trends in annoyance and to inform local policy. Preference for the two questions is fairly evenly split, as discussed above. One of the reasons ISO/TS 15666:2021 set out the advantages and disadvantages of the two questions was to invite further discussion about how and when the field could shift to the use of one question. That time is now. The authors of this paper are unanimously aligned with their preference for the verbal 5-point scale, for the reasons set out above. However we recognise that a decision should follow from a serious debate within the relevant ISO Working Group, and should be the focus of the next revision of ISO/TS 15666. During a period of transition, the methods discussed earlier in the paper could support the historical comparison of data, with some caveats.

Further, there are still many instances where the format of the question does not comply with ISO/TS 15666, again often due to precedent and historical use. The field cannot continue to misuse' ISO/TS 15666: it should be used as published, accompanied by the reporting checklist [14]. The time to influence the format of ISO/TSn15666 is during its revision via national standards bodies, and not in individual surveys. This does not constrain the use of local or novel questions in relation to annoyance, as ISO/TS 15666 allows for additional questions after the standard question(s) have been asked.

CONCLUSION

1. Three different methods for calculating %HA that are not comparable lead to confusion and mixed messages, particularly amongst policy makers, the industry trying to manage noise impacts and community groups affected by noise.
2. We argue that HA_{vw} should no longer be included in future revisions of ISO/TS 15666. It was originally proposed as an attempt to align %HA from 5-point verbal scale to %HA from the 11 point scale, where needed. However, studies have shown that HA_{vw} is not comparable to HA_N. Perhaps more importantly, it sends a message that the noise and health research community believes that three out of every five people that state they are "very" bothered, disturbed or annoyed are, in fact, not "highly annoyed" by noise. Or, in the words of Brink et al. [18]:

   "taking the verbal judgments of survey respondents as serious is clearly less arbitrary than the setting of a numerical cutoff point".
3. It is time to pick one question to assess annoyance for ISO/TS 15666. Both the 11-point and 5-point scales continue to have strong support amongst the noise and health community, with valid arguments from each side. However, when it comes to calculating the percentage of people highly annoyed, we argue that the emphasis should be on the semantic aspect. This is best aligned with the judgements of survey respondents, and with how non-specialists (e.g. policy makers, industry and community groups) understand the concept of "highly annoyed". It is also the way how the severity of annoyance as a health outcome was presented in public surveys (using the Disability Weight approach). The original ICBEN work showed that the intensity scores of words such as "considerably", "substantially", "importantly" and "significantly" are not captured by the cut-off currently implicit in HA_N. We propose that a future revision of ISO/TS 15666 recognises HA_V as the reference measure of "highly annoyed". If a HA_N method is still deemed necessary, then the cut-off should be adjusted to better align with HA_V, and not the other way round.

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Prominence and annoyance of impulsive sounds - An updated objective method

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ABSTRACT

The assessment of prominence and annoyance of environmental impulsive noises has long presented a challenge. Binary penalty systems (in Denmark a 5 dB on/off penalty) fail to capture the subjective response e.g. with varying prominence and periods of occurrence. A measurement method was developed in year 2001 for the Danish Environmental Protection Agency (DK-EPA) and adopted as a NORDTEST guideline and later as an ISO/PAS method. Practical use and research indicate an overestimation of penalties for high-onset-rate impulses.
To improve the method, DK-EPA initiated a three-phase project. 1: Gather practical information. 2: Lite-rature study of the latest international results and 3: Testing the method in listening tests. Furthermore, an opinion survey was conducted among practitioners and authorities to clarify the administrative rules.
Based on the first phases, listening tests (N=23) on prominence and annoyance were conducted with 80 real-world binaural recordings of environmental sounds presented through calibrated headphones. Annoyance ratings were obtained with the ICBEN scale, and the corresponding penalties were deducted from comparison with annoyance of road traffic noise. The results were merged with findings of a Finnish listening test (N=32) with 33 synthetic transient sounds and with the earlier Danish study (N=17) with 34 environmental impulsive sounds.
The method was optimized for a better fit to the listening tests, yielding an average reduction of 3.3 dB of the penalty with a maximum penalty of 9 dB. Administrative rules were specified and a computation model for the reduction of prominence of impulses with distance was defined.

BACKGROUND

Environmental noise with impulsive sounds is perceived as more annoying than sounds at the same level (L_{Aeq}) without impulses. When assessing the noise exposure, a penalty / addition is made to the measured L_{Aeq} level to compensate for the extra annoyance.

An objective measurement method for assessment of prominence and annoyance of environmental impulsive was developed in year 2001 for the Danish Environmental Protection Agency (DK-EPA) [1], [2] and adopted as a NORDTEST guideline [3] and later as an ISO/PAS method [4]. The method is not intended for measuring the prominence of gunfire and high-energy impulsive sound.

The method predicts the perceived prominence of the impulses in the immission point, by analysing an A-weighted measurement with time weighting F of the onset rate and level difference of the onset of the impulses.

The method has been used in Denmark since 2001 as support for subjective assessments for a 5 dB penalty and has been included in several proficiency testing's see e.g. [5]. The use of the method and new Finnish research [6] have indicated an overestimation of the penalties in the original method for high-onset-rate impulses.

To improve the method, the Danish Environmental Protection Agency initiated a three-phase project. 1: Gather practical information, [7]. 2: Literature study of the latest international results, [8]. 3: Testing the method in listening tests, [9]. Furthermore, an opinion survey was conducted among practitioners and authorities to clarify the administrative rules [10]. The reports are in Danish with English summaries and can be downloaded from the Reference Laboratory website.

LISTENING TESTS

As part of the project, a new listening test (DK2 see below) was carried out. To find the relevant penalty for the extra annoyance, the impulsive noise was compared to the annoyance of a constant reference noise. The listening tests from the original project (DK1 [1], see below) and from a Finnish study (FI [6] was also included in the optimization of the measurement method. The optimized method, which is referred to in the succeeding clauses, is described in the next chapter. In the next clauses "predicted" means that the results are calculated from physical measurements and analysis of the stimuli according to the objective method.

Danish listening test, DK1

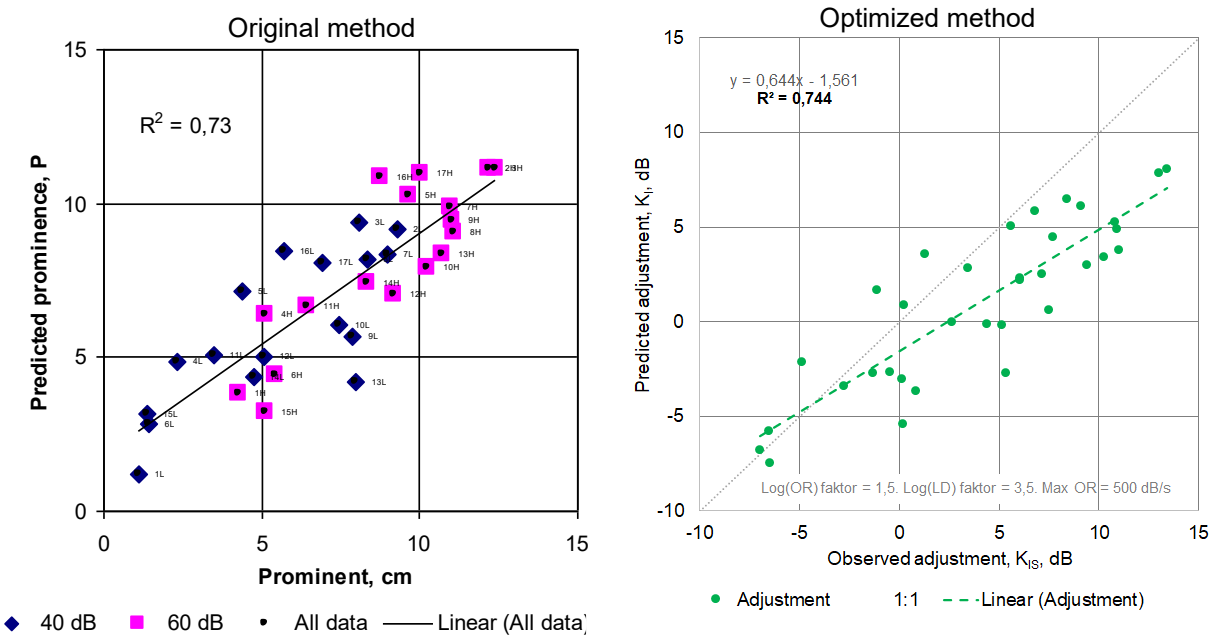

Figure 1: Results from listening test DK1.
Left panel: The measured (i.e. rated by the listeners) prominence (x-axis) and the predicted prominence calculated with the original impulse method (y-axis). The stimulus groups were at L_{Aeq} = 40 and 60 dB. Right panel: The "Observed" adjustments, K_{IS}, are calculated from the observed prominence and the formulas in the original method. The predicted prominence is calculated with the constants for the optimized method and converted into adjustments K_I.

The 34 stimuli for this listening test from 2001 came mainly from real noise sources in the environment, which were recorded with simulated binaural technique and reproduced over open headphones in a test having 17 listeners.

The sound samples (stimuli) were 30 seconds long, had onset rates of 2-667 dB/s and level differences of 1-37 dB. They were presented with L_{Aeq} levels at 40 and 60 dB.

The listeners rated prominence and annoyance. There was no reference noise. In the data processing for this paper the prominence was converted to an adjustment according to the formula in the original impulse method. This listening test is reported in reference [1].

It can be seen from Figure 1 that the proportion of explained variance, R^2, is slightly higher for the optimized method than for the original method.

Finnish listening test, FI

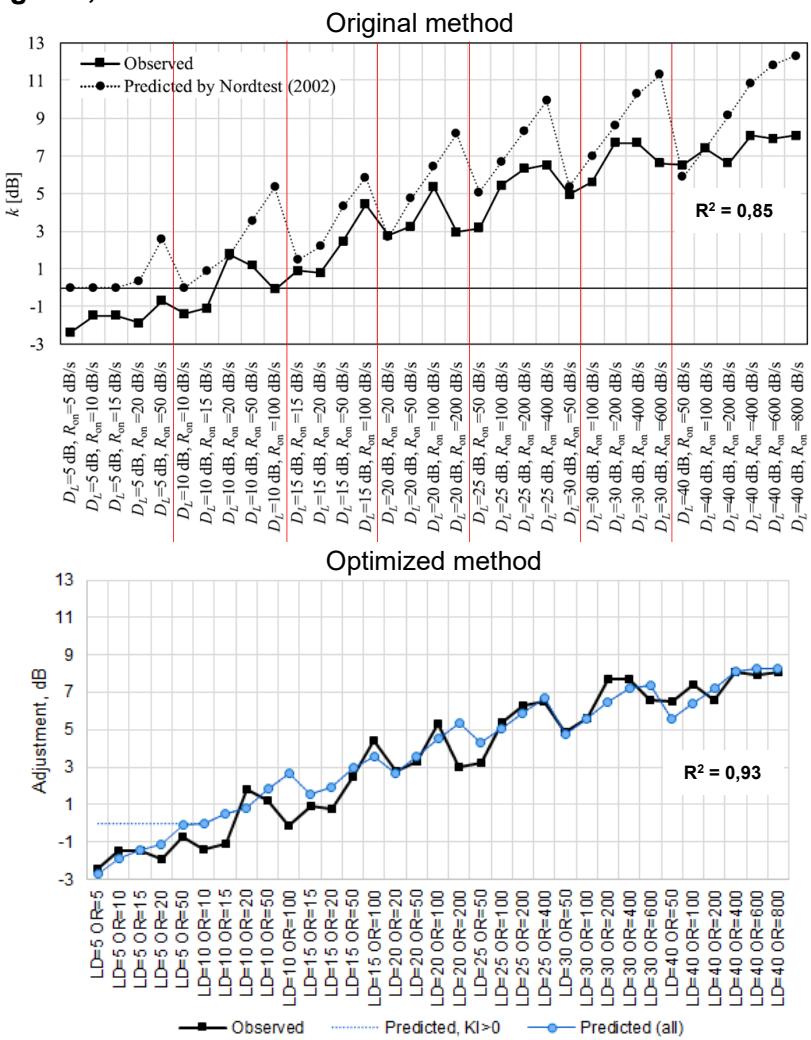

Figure 2: Results from listening test FI.
Upper panel: The impulse adjustment observed in the Finnish listening test for impulses with spectrum S1 and the adjustment calculated (predicted) the original method. Figure from [6]. The level difference classes (DL) are highlighted with red lines. Within each class, the stimuli are ordered by increasing onset rate (R_{on}). The 95 % confidence intervals for the observed data are approx. 2 dB.
Lower panel: Same data whereas the predicted adjustments are calculated with the optimized method.

The 33 stimuli for this listening test from 2020 were artificially generated noise samples reproduced over open headphones in a test with 32 listeners.

The stimuli were 18.5 seconds long and had slopes of 5-800 dB/s and level differences of 5-40 dB. They were presented at L_{Aeq} = 55 dB.

The listeners rated annoyance. When compared to a stationary reference noise with the same spectrum as the impulse noise, the measured annoyance was converted into an annoyance equivalent adjustment for the impulses.

From Figure 2 it is seen that the original method overestimated the adjustments for impulsive sounds with high onset rates.

When the physical measurements were calculated with the optimized method (lower panel) it is seen that the optimized method provides a significantly better adaptation of the calculated physical adjustments (predicted) to the subjectively measured (observed). Additionally, there are only a few stimuli where the calculated physical adjustment, K_I, deviates more than approx. 1 dB from the subjectively measured, K_{IS}. This is within the 95 % confidence intervals of the observed data.

The optimized method gives a higher proportion of explained variance, R^2 = 0.93, than the original method, R^2 = 0.85.

Danish listening test DK2

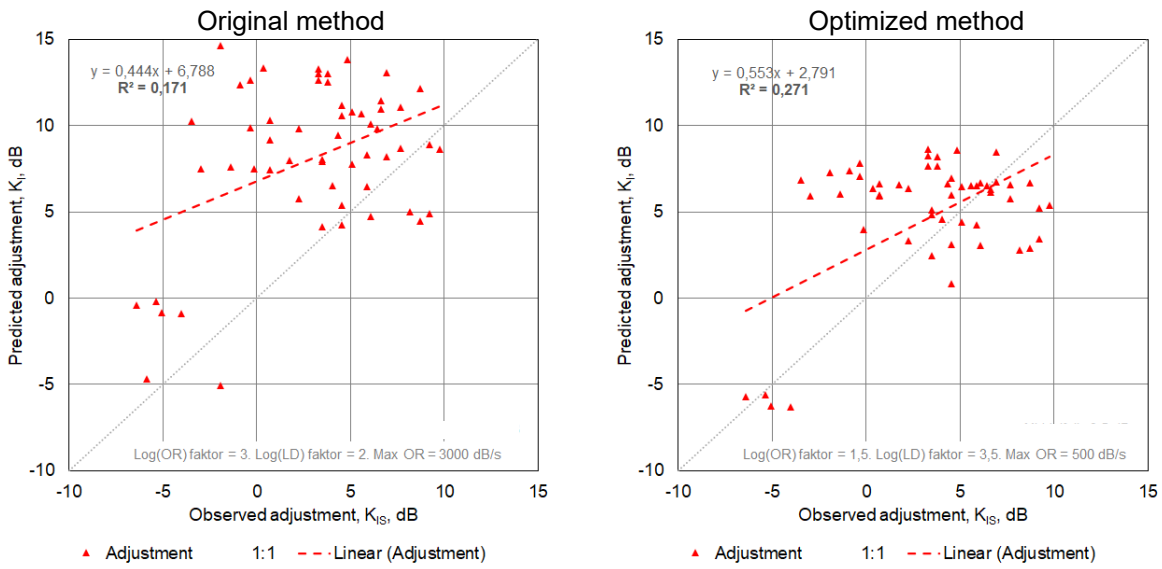

Figure 3: Results from listening test DK2.
Left panel: The observed (rated by the listeners) adjustment, K_{IS}, (x-axis) and the predicted adjustment, K_I, calculated by the original impulse method (y-axis). Both groups L_{Aeq} = 40 and 60 dB are shown.
Right panel: The predicted adjustments are calculated with the optimized method.

The 80 stimuli for the listening test from 2023 all originated from real noise sources in the environment. They were recorded with artificial head technique (HATS) and measuring microphones (free field recordings). Recordings were made in distances from the source mostly at 10 m (3-15 m), and the levels were adjusted to L_{Aeq} = 60 dB.

The 40 dB stimuli were created from the 60 dB stimuli corresponding to a 100 m distance. The frequency dependent attenuation was calculated with Nord2000, [11], [12]. The width of the soundscape was decreased by mixing the right and left channel according to [13]. Finally, the

levels were adjusted to L_{Aeq} = 40 dB, and a recording of noise 650 m away from an 8 lanes motorway was added as background noise at a level of L_{Aeq} = 30 dB.

The HATS stimuli were reproduced over open headphones to the 23 listeners. The physical measurements were made on free field recordings converted from the HATS stimuli.

The sound samples were 20 seconds long, the impulses had onset rates of 14-2670 dB/s, level differences of 0.2-44 dB. They were presented with L_{Aeq} levels at 40 and 60 dB. Level recordings of the stimuli can be seen in [9].

Listeners rated prominence and annoyance. When compared with a stationary reference noise (simplified back-ground traffic noise [14]), the measured annoyance was converted into a noise-equivalent adjustment for the impulses. The reference noise and the impulsive noise types did not have the same spectrum.

From Figure 3 it is seen that the R^2 between the observed and the predicted data for DK2 is much less than for DK1 and FI. Since the recordings originate from real life, with easily identifiable sound sources, other audible characteristics, as well as the listeners' attitudes towards the sources, may also influence the annoyance besides the prominence of the impulses. Nevertheless, it is seen that the optimized method provides better results than the original method.

Negative adjustments

As seen from the graphs in the former clauses negative adjustments appear. They shall not be a part of the method but are enclosed in the analysis to benefit from the information from these data.

The negative adjustments means that there are sounds that are less annoying than the reference sounds. In the Finnish test, sounds with slow variations like waves were less annoying that the constant reference sound. In DK2 sounds from motorways were less annoying than the simplified background noise used as reference sound. In this case the difference could be explained by a difference in loudness level for the sounds with the equal L_{Aeq}.

It was also found that the dose-response functions between L_{Aeq} and the annoyance were different in DK2 and the Finnish listening test.

These observations indicate that the choice of reference sound has a direct influence on the resulting adjustment. Thorough considerations on which reference sounds to use (in general) are therefore important.

CONCLUSION

Based on the listening tests results, the objective measurement method was optimized for:

- maximizing R^2 between observed and predicted adjustments
- minimizing the average error of the datapoints
- a 1:1 relation between the observed subjective and the predicted adjustments
- aligning the maximum subjective and the maximum predicted adjustments.

On all these parameters the optimized method performs better than the original. Especially the Finnish results indicates that the principle of the method is in accordance with the perception of the annoyance of the impulses and that the relation between onset rate and level difference is more in line with perception in the optimized method than in the original method.

A small level dependency of the adjustment was found, but the basis is too weak for complicating the method by introducing a level dependency.

In the optimized method the prominence of the impulses, P, is calculated from:

$$P = 1.5 \cdot \log(\text{onset rate}/[\text{dB/s}]) + 3.5 \cdot \log(\text{level difference}/[\text{dB}])$$ (see footnote[1])

A limitation of the onset rate of 500 dB/s has been introduced in the calculation of P. The penalty/addition to L_{Aeq} is calculated from the predicted prominence.

In average, the optimized method gives 3.3 dB less adjustments than the original method and it corrects for the overestimation of impulses with high onset rates which the original method gives rise to. The optimized method limits the maximum adjustments to less than 9 dB. Analyses of DK1 and DK2 showed that the number of impulses in the stimuli was not significant for the annoyance of the stimuli (duration 30 and 20 seconds).

THE OPTIMIZED MEASUREMENT METHOD

The optimized measurement method is described in full in a draft guideline [15] (in Danish) including a method for calculating the decrease in the prominence of the impulses with distance and background noise level. A summary is given below:

Definitions

Impulse event: The sudden onset of a sound is defined as an impulse. An impulse event is an activity which, within a few seconds, produces one or more impulses that are so prominent that they can give rise to an adjustment / penalty.

Assessment time interval: The parts of the reference period where adjustments are given to the measured L_{Aeq}. An assessment time interval is 30 minutes, which is determined freely around the impulse events, so it includes as many prominent impulse events as possible. There may be several assessment time intervals within a reference period.

Stationary noise: In this context, the continuous part of the background noise, which together with any stationary noise for the activity under investigation, can mask the impulses at the point of reception ("receiver point / immission point").

Normal operating mode: Regularly occurring activities when the activity is in operation.

Administration

If there are no audible impulses in the reception point, no adjustment should be made. If the noise contains one or more audible impulses, an addition, K_I is given to L_{Aeq} in the assessment time intervals where the impulses occur. The adjustment is determined based on the most prominent impulse in an assessment time interval based on a normal operating state of the activity.

During the day and evening period:

- More than one impulse event is required to give an adjustment.
- Door slams from cars at the activity are exempt from impulse adjustment.

During the night period:

[1] The constant for log(onset rate) was changed from 3 and the constant for log(level difference) is changed from 2 in the original method, which had no limitation on onset rate.

- A single impulse event is enough to give an adjustment.
- Door slams from cars at the activity are not exempt from impulse adjustments and are treated like other impulses from the activity.

It is recommended to determine the adjustment based on an objective measurement at the reception point, see section 3. However, the adjustment can be based on a subjective assessment of how prominent impulses are heard over the stationary noise at the reception point, considering both the rate and magnitude of level changes. An adjustment of 3 dB is given for impulses that are just audible. An adjustment of 6 dB is given for clearly audible impulses and an adjustment of 9 dB for impulses that are very prominent in the overall sound image.

Subjective assessments and objective measurements of the prominence of the pulses must be performed under correct weather conditions and representative background noise conditions in the immission/calculation points. This should be stated in the measurement report.

The objective measurement method

The original objective measuring method is described in NORDTEST ACOU 112 [3] and ISO/PAS 1996-3 [4]. The acoustic measurements and analyses are the same for the optimized method as described in these references. A few key points from these will be noted, but there are also a few essential changes in the final calculations that will be mentioned here.

Definitions

Sound pressure level, L_{pAF}: The frequency-weighted and F time-weighted sound pressure level

Impulse: The sudden onset of a sound.
The character and prominence of the impulse at the immission point depends on the character of the emitted sound, the distance and propagation path from the sound source (including meteorological effects) and the background noise. Therefore, the impulsiveness of a sound is characterized by the onset of the sound independently of the category of the sound source.

Onset: The contiguous part of the positive slope of the time history of L_{pAF} where the gradient exceeds 10 dB/s.

The starting point of an onset is the point where the gradient first exceeds 10 dB/s. The end point of an onset is the first point after the starting point where the gradient decreases to less than 10 dB/s.

Irregularities (on the onset) shorter than 50 ms are excluded.

Level difference, LD: The difference in decibels of L_{pAF} between the level of the end point L_e and the level of the starting point L_s of the onset.

Onset rate, OR: The slope in decibels per second of the straight line that gives the best approximation to the onset between the starting point and the end point (linear regression analysis).

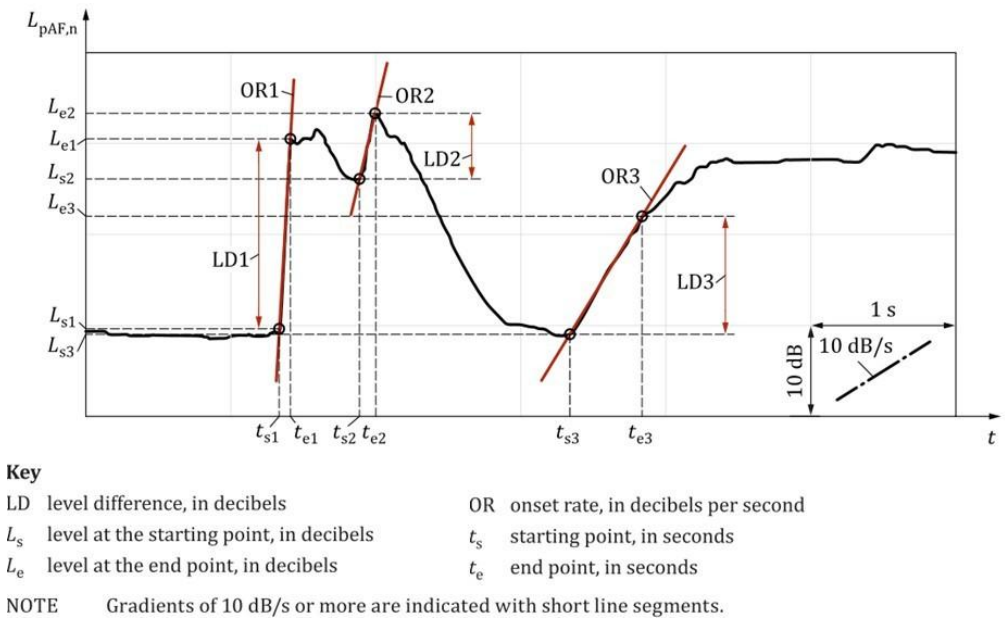

Figure 4: Analysis of the time history of the A frequency-weighted and F time-weighted sound pressure levels, from [4].

Measurements

In references NORDTEST ACOU 112 [3], ISO/PAS 1996-3 [4] and the draft guideline [15] specifications on the acoustic measurements and analysis are given.

Prominence, P

The prominence of the impulses, P, is calculated from:

$$P = 1.5 \cdot \log (OR/[dB/s]) + 3.5 \cdot \log (LD/[dB]) \qquad (1)$$ [2]

- If the slope is greater than 500 dB/s, it is set to 500 dB/s.
- If the level difference is greater than 50 dB, it is set to 50 dB.

This means that the adjustment K_I for the prominence of the pulses cannot exceed 9 dB.

The impulse with the highest value of P in the half hour in question gives the final result for this half hour.

Adjustment K_I to L_{Aeq}

For sounds with onset rates larger than 10 dB/s, the adjustment K_I, based on the prominence P, is calculated as given by:

$$K_I = 1.8 \cdot (P - 5), \text{ for } P > 5, \quad K_I = 0 \text{ for } P \leq 5 \qquad (2)$$ [3]

Where K_I is the adjustment, expressed in dB.

[2] The constant for log(onset rate) was changed from 3 and the constant for log(level difference) is changed from 2 in the original method, which had no limitation on onset rate.
[3] This is unchanged from the original method

Note:
The general form of formula (2) is: $K_I = k_3 \cdot (P - k_4)$, for $P > k_4$, $K_I = 0$ for $P \leq k_4$. The constant k_3 gives the inclination of the correlation between K_I and P, and k_4 defines the lower limit for adjustment to L_{Aeq}. The values of the constants k_3 and k_4 have been determined to give correspondence with the extra annoyance reported in the literature for different kinds of noise sources. As the annoyance depends on the level and characteristics of the noise, the kind of sound source, the context and social factors, and as the adjustment K_I is meant to compensate for the extra annoyance from the impulses, other values of k_3 and k_4 that depends on the category of sound source and situational factors may be relevant. An example: Although the method is not intended for measuring the annoyance of gunfire and high-energy impulsive sound it has been found, that changing k_3 from 1.8 to 2.1 gave a good fit to listening test results on shooting noise in reference [16].

During an assessment time interval of 30 min, the adjustment for the one event with the highest value of P occurring during this time is assessed. For reference time intervals of less than 30 min, the assessment time interval should be aligned with this reference time interval and reported. The rating level for a reference time interval is determined as the energy-average of the rating level of each assessment time interval.

Accuracy

In reference [15] it is concluded that the standard deviation of the K_I when different laboratories perform objective analyses is between 0.5 and 1 dB. In addition, there is the uncertainty of the measurements in the field, which must be assessed based on the uncertainty of the operating condition of the impulse sources, the sound propagation and the background noise.

CALCULATION OF IMPULSE PENALTY

In a planning situation, where measurements in the immission points are not an option, it is relevant to be able to calculate if a penalty should be given to the noise level from the sources under consideration. In an appendix in reference [15], a method by which the impulse penalty at an immission point can be calculated from the steepness of the impulses at the source, the calculated maximum value (L_{pAmax}) at the point and the background noise level at the point is specified. The method has been developed theoretically and tested on relevant sound files, but it has not been verified by measurements in the field.

Calculation Method

The method is based on the following input data:

1. The onset rate of the impulses at the source, which can be measured at the actual source or equivalent sources.
2. The maximum values at the immission point, L_{pAmax} with time weighting F, which can be calculated using the Nordic method for sound propagation based on the maximum values of the impulses measured at the source.
3. The A-weighted background noise level at the immission point, measured at the actual site or equivalent locations.

The following concepts are included:

1. OR_{Source}: The onset rate measured in an immission-relevant direction close to the source according to the impulse method.
2. LD_{Nom}: Nominal level difference at the immission point: L_{pAmax} minus the background noise level.
3. OR: The onset rate at the immission point according to the impulse method.
4. LD: The level difference at the immission point according to the impulse method.

The background noise level at the immission/reception points is specified as the L_{Aeq} level during frequent periods of low background noise when the impulses occur.

The impulse adjustment (penalty) can be found in Figure 5.

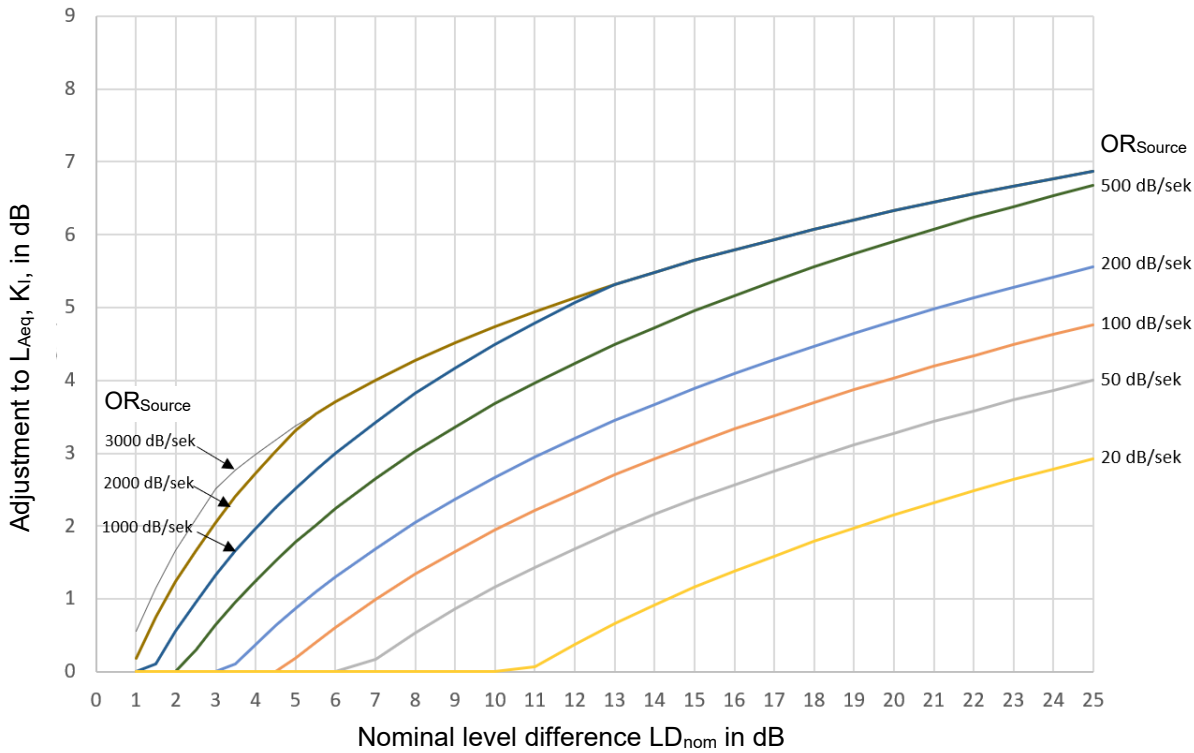

Figure 4: Determination of the impulse adjustment K_I based on the nominal level difference LD_{nom} and the onset rate of the impulses at the source OR_{source}.

The background for - and the formulas behind - Figure 5 can be found in reference [15].

Expected accuracy

Based on tests conducted with artificial impulses and audio files, it has been found that the error in the calculation of K_I is generally less than 0.5 dB. However, for LD_{Nom} < 2 dB and OR_{source} > 1000 dB/s, the error can be up to 1.2 dB.

The standard deviation for all errors on K_I in the performed tests is 0.25 dB, which, with a coverage factor of 1.65, corresponds to an uncertainty of 0.4 dB. Added to this is the uncertainty of the measurement and calculation of L_{pAmax} and the L_{Aeq} of the background noise level, which are included in the formulas for calculating K_I.

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NASA's plans to assess annoyance caused by supersonic overflights of the X-59 aircraft

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ABSTRACT

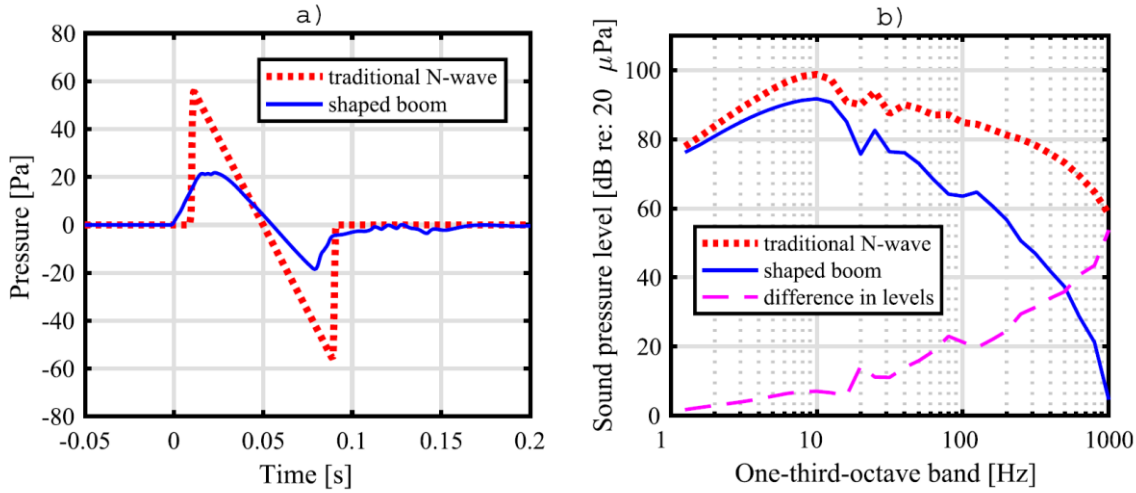
In its mission to expand knowledge and improve aviation, NASA conducts research to address sonic boom noise, the prime barrier to overland supersonic flight. For half a century, civilian aircraft have been required to fly slower than the speed of sound when over land to prevent sonic boom disturbances from impacting communities under the flight path. However, reduced sonic boom noise levels may be achieved via new aircraft shaping techniques that limit the merging of shockwaves generated during supersonic flight. NASA's piloted research aircraft, the X-59, was built to demonstrate reduced sonic boom noise during supersonic flight and took its first flight in October 2025. After the completion of flight testing to ensure the aircraft performs as designed, NASA will begin a national campaign of supersonic flights over communities to collect data on how people perceive the noise from this new design. The data will support the efforts of national and international noise regulators to develop new standards that would allow supersonic flight over land at reduced noise levels. This paper summarizes key research results on which the X-59 community surveys are based, as well as current plans for NASA's X-59 community survey campaign.

INTRODUCTION

The United States (US) National Aeronautics and Space Administration (NASA) envisions a future in which faster air travel is available to all, meaning less time en route and more time at destinations. Current regulations that prohibit civil supersonic flight over land1 are the prime barrier to this vision. When this speed restriction was first introduced a half century ago, it was intended to prevent sonic boom noise from disturbing communities.

In recent decades, the research community has developed new designs for supersonic aircraft that produce what is called a shaped boom, with reduced noise relative to a typical sonic boom (traditional N-wave), as shown in Figure 1. Simulated shaped booms are rarely perceived as annoying, whether in laboratory tests or field tests. However, shaped booms from a purpose-built supersonic aircraft have never been tested over a representative population to gather community response. The community survey campaign phase of the NASA Quesst mission will generate these specific data to support the development of supersonic overflight noise certification standards, not based on speed, but on noise level.

Figure 1: Simulated (a) time histories and (b) one-third-octave band sound pressure levels for a



traditional N-wave sonic boom and a reduced noise signature (i.e., a shaped boom).[2]

To put shaped booms in context with other impulsive sounds, the graphic in Figure 2 shows a range of impulsive environmental sounds arranged by loudness. The NASA X-59 was designed to achieve a shaped boom, which is comparable to distant thunder or a car door shutting from across the street. This sound is much lower in level than the sonic boom from the Concorde, which is comparable to nearby thunder or a car door shutting from inside the car.

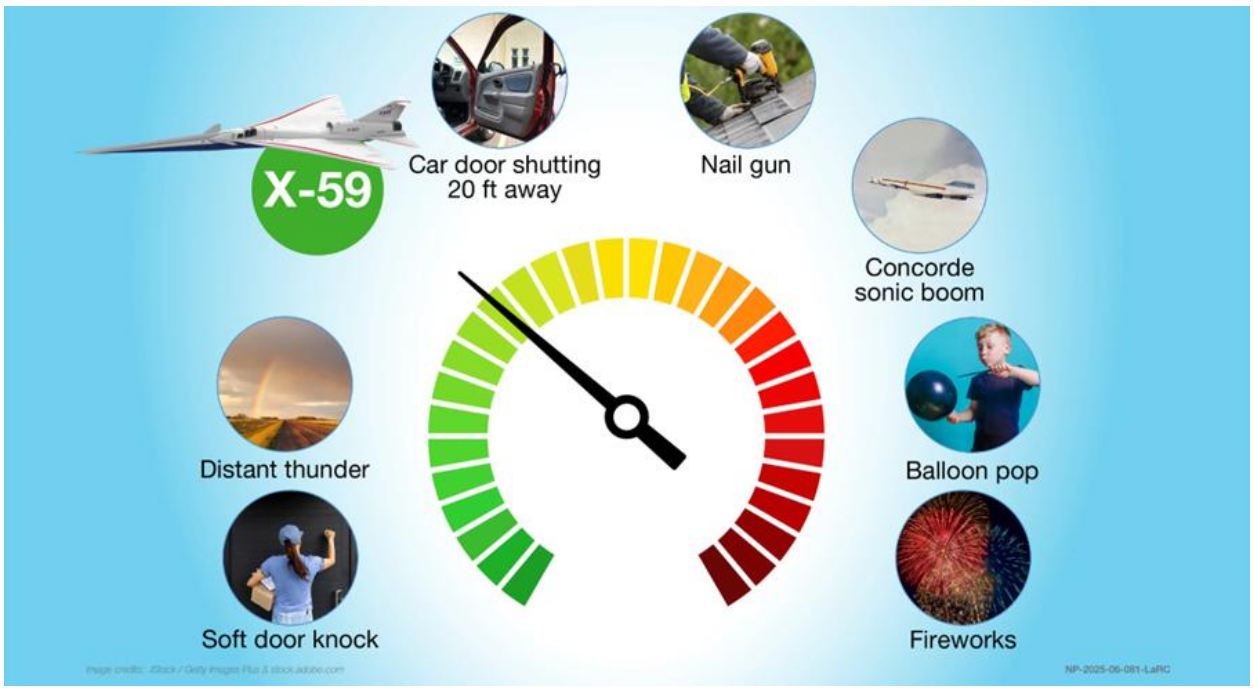


Figure 2: Comparison of sound levels among X-59, Concorde sonic boom, and other impulsive environmental sounds.[3]

PAST RESEARCH

Historic Studies

In the early decades of supersonic flight, many studies were conducted both in the laboratory and in the field to learn more about human response to sonic boom noise.4 Two influential studies were community surveys in St. Louis and Oklahoma City, which lasted a half year each. In St. Louis there were 76 sonic booms, and in Oklahoma City there were more than 1200 booms. From these surveys, two key results were identified: 1) conventional sonic booms were not publicly acceptable, and 2) of the factors shaping human response, indoor annoyance was the most important. Many decades of research and careful study have led researchers to the conclusion that the loudness and annoyance of supersonic flight can be reduced through careful design of the aircraft shape. Beginning in the early 2010s, a new generation of research has been undertaken to better understand community response to reduced sonic boom noise. The initial community surveys of this era used an F-18 performing a low-boom dive maneuver to simulate a shaped boom, but X-59 will fly steady and level in its survey campaign because it is a low-boom airplane. A summary of NASA community surveys in this timeframe is shown in Table 1.

Table 1: Summary of NASA community surveys.

Title	Aircraft / Flight maneuver	Location	Year	Number of Survey Participants	Number of noise events	Research Goal
Small Community Survey	F-18 / low-boom dive	Edwards, CA	2011	100	110	Pilot Study
Large Community Survey	F-18 / low-boom dive	Galveston, TX	2018	500	52	Risk Reduction
Survey Methods Test	n/a	Nashville, TN	2023	500	n/a	Risk Reduction
X-59 Community Survey Campaign	X-59 / steady level flight	Multiple, TBD	Planned for late 2020s	1000 per site	~80	Data for Regulators

Small Community Survey

In 2011, a small community survey was conducted over ten days at Edwards Air Force Base in California on approximately 100 participants split into two panels.[5],[6] The survey was a pilot study to demonstrate research methods and compare survey modes to investigate prompt responses to shaped sonic boom events. Each day, there were between 4 and 13 sonic booms at various amplitudes during daytime hours. A NASA research aircraft flew a supersonic dive maneuver to simulate a shaped boom. Three survey modes were employed: paper, web, and smartphone. All survey data modes were approximately equally successful, with no single mode clearly superior in terms of completion rate or participant experience. One lesson learned was to separate noise exposures by at least 20 to 30 minutes to ensure that responses could be reliably associated with specific noise events. Manual triggering of

recording on the noise measurement kits was used for data collection, but an automated recording and boom-finding algorithm was developed and recommended for the future so kits could be operated in auto-mode without dedicated triggering.

Large Community Survey

In 2018, a large community noise survey was conducted over a two-week period in Galveston, Texas[7] using a NASA research aircraft flying a supersonic dive maneuver to simulate a shaped boom. The research goal was risk reduction by demonstrating that NASA could successfully engage with a community to execute a community noise survey using a NASA research aircraft. The lessons learned included conducting early community engagement, with separate tailored engagements for local air traffic control, elected officials, the public, and survey participants. In terms of the survey, reminder messages sent to survey participants helped improve survey completion rates. For all data collected, the need for automation in data reduction and analysis was identified, especially if in the future multiple community tests would be planned within a single calendar year.

Survey Methods Test

In 2023 a multi-week survey methods test was completed with members of the public in Nashville, Tennessee.[8] The goal of this test was risk reduction by verifying that the survey methods developed for X-59 tests would function as desired. Because there were no flyovers by X-59 or other supersonic aircraft, respondents were asked about their reactions to noise from ongoing subsonic aircraft operations. The address-based sampling method enabled a representative sample of 800 residents to be recruited from an area equivalent in size to an X-59 survey site. A graduated incentive structure kept respondents engaged, with higher incentives for higher survey completion levels and for each subsequent week of the test. Location data were also collected from respondents since they will be needed to estimate individual noise exposure for each noise event from X-59. The survey methods test enabled successful execution of the full survey process, with response rates consistently between 40% and 60%, which exceeded expectations. Some additional lessons learned included the importance of automation in critical processes and the vulnerability of systems to network and server problems.

PLANNED RESEARCH

Scope of X-59 Community Survey Campaign

The primary research goal of the X-59 community survey campaign is to collect representative community response data to support the development of supersonic overflight noise certification standards. The data must describe the dose-response relationship between annoyance and noise exposure. Additional survey questions will assess the following secondary research goals: 1) Assess the effects of indoor noise-induced rattle sounds and vibration on dose-response relationships, 2) Assess the effect of listening environment (home vs. work vs. somewhere else, indoor vs. outdoor, indoor with windows open vs. closed, and urban vs. rural) on dose-response relationships 3) Assess the effect of time-of-day on dose-response relationships (daytime vs. evening), and 4) Assess the prevalence of “startle” (i.e. the feeling of sudden shock or alarm), which was a major component of annoyance in historic sonic boom community surveys.

To collect nationally representative dose-response data, NASA will conduct community surveys at up to five sites representing different geographic regions of the US. The sites will also differ in terms of racial/ethnic composition and levels of urbanicity. For each community

survey, NASA anticipates conducting up to 6 supersonic overflights (single events) per day, totaling an estimated 80 such events per survey over a month. This number of overflights and month-long survey duration have been chosen to give survey participants time to adapt to the new sounds. For each community survey, NASA intends to acquire survey responses from a probability-based sample of at least 1000 participants.

As described in Rathsam et al.,[9] the need to focus survey objectives means that certain data will not be collected. For example, the effects of nighttime supersonic overflight noise exposure, including possible sleep disturbance, will not be studied in the current timeframe due to a combination of operational and safety considerations. Community response to focus booms created when the X-59 accelerates into supersonic flight will not be acquired. The effects of reduced noise supersonic overflights on animals will not be tested due to the low likelihood of harmful effects. While sonic booms are the key barrier, they are not the only barrier to viable commercial supersonic flight over land. Other barriers to supersonic flights to be addressed beyond the Quesst mission include takeoff and landing noise in airport communities, high-altitude emissions during supersonic flight, aircraft efficiency in terms of lightweight structures and low drag, and affordability.

The following sections illustrate the high degree of technical consideration across a range of methodological topics to maximize the robustness and validity of the X-59 community survey data.

Dose-Response Modeling

The dose-response model will be summarized via a quantitative relationship, or a summary curve, that describes the fraction of people highly annoyed as a function of noise exposure. Annoyance is assessed in the survey as an ordinal variable on a 5-point verbal scale. By convention, the 5-point scale is converted into a binary outcome of highly annoyed vs not highly annoyed.[10] Noise exposure is a continuous variable, estimated based on the participant's reported location during each flyover. Separate dose-response models are planned for single-event exposure, or single overflights, and for cumulative exposure from multiple flyovers throughout the day.

A common modeling approach is the simple logistic regression model, in which the probability of being highly annoyed depends only on the noise exposure level. The simple logistic regression model can be made more sophisticated by including other covariates, such as demographic variables like age, race, and ethnicity; housing variables like type of dwelling (single-family home, apartment, etc.); or location variables like urbanicity and population density, as well as interaction effects.

Some individuals may have a higher or lower threshold for annoyance compared to other individuals despite having the same demographic, housing, and/or location characteristics. While the simple logistic regression model described above includes the effect of these characteristics, it does not account for additional individual-level variation not captured by other covariates. For this reason, a multilevel logistic regression may be introduced to account for this effect.

Other possible modeling approaches include ordinal regression and multilevel ordinal regression,[11] which model the cumulative probability of responding at each annoyance level. Another model under consideration is a two-stage model. The first stage models the probability that a participant ever responds as highly annoyed given demographics, and the second stage models the probability of high annoyance, but is fit only on the participants who responded at least once as highly annoyed.[12] This collection of potential analysis techniques serves as a toolchest to be drawn from once the data are collected. Multiple modeling methods will be evaluated on the dataset for the sake of comparison.

Measurement Error Corrections

One factor that can distort a dose-response curve is measurement error.[13] Measurement error is the difference between the observed, or measured, noise dose and its true, unknowable value. When measurement error is not properly accounted for, it can artificially flatten a dose-response curve, causing overestimated annoyance at low noise doses and underestimated annoyance at high noise doses.

Several techniques exist to correct for measurement error, including regression calibration, simulation extrapolation (SIMEX), structural Bayesian hierarchical models, and data cloning. A NASA review found that structural Bayesian hierarchical models may be most readily applicable to X-59 community surveys because of their flexibility and ability to propagate uncertainty from the individual level to the population level.[14] The Bayesian techniques were also demonstrated by Erciulescu and Opsomer.[15] Measurement error will be estimated for X-59 shaped sonic boom measurements starting in the acoustic validation phase, prior to community testing, and the techniques described above will be exercised on the X-59 community survey data to identify whether measurement error is present and, if so, to correct for it.

Control Condition

A control condition is defined as a condition in an experimental design that does not involve exposure to the treatment or intervention under study.[16] For the X-59 community survey, a control condition is planned to assess annoyance in the absence of X-59 flights, as well as during X-59 flights. Including a control condition is foundational in research experiments with human subjects and necessary for valid inferences.

While specific analysis techniques for the control condition data are under development, in general the data will help guide the interpretation of dose-response curves. For example, a control condition was included in the large community study described in the previous section, and the result was that some participants were highly annoyed even when no flight occurred. The proportion highly annoyed under the control condition presents a plausible lower limit on annoyance that can be reliably assessed and attributed to noise from the supersonic flight. A similar analysis is planned for the control condition data during the X-59 community survey.

Carryover Effects

Carryover effects occur when a person's exposure to a previous experimental condition influences their response to the current experimental condition. Carryover effects can be a source of response bias, causing the reported response to differ from the actual response. While it is rarely possible to fully avoid carryover effects, their presence or absence can sometimes be confirmed via analysis, and some methodological steps can be taken to reduce their severity. For example, randomizing the presentation order of noise dose levels can help minimize potential effects of presentation order.

Other potential carryover effects include decisional carryover, habituation, and contrast effects. Decisional carryover is the effect of previous annoyance responses on the annoyance rating of the subsequent booms. Habituation is when a participant becomes acclimated over time and becomes less annoyed, and a contrast effect is the opposite, when a participant becomes more annoyed as time progresses. NASA's choice of a monthlong duration for each X-59 community survey was based on judgment rather than data and was intended to give participants time to adapt to the new noise.

In the X-59 community surveys, where aircraft operational considerations and safety are the top priority, and factors such as weather cannot be controlled, the methodological steps that

can be taken to reduce carryover effects are limited. However, analyses will be undertaken to identify potential carryover effects in the data, some of which were demonstrated notionally by NASA authors on laboratory data.[17]

Combining Multiple Survey Sites and Generalizing to the Population

To support the development of noise limits, a single representative dose-response curve is desired rather than multiple curves. However, to be representative, the curve must stem from surveys conducted at multiple geographically diverse locations. Therefore, two methodological processes are needed: first, a process to determine whether combination of multiple community surveys is warranted by the data (i.e., whether the data are consistent enough to justify merging data); and second, a process to combine the survey results into a single dose-response curve.

A NASA report reviewed relevant literature and provided several tools to assess the data similarity among two or more survey sites.[18] The first tool is the confidence band overlap, which divides the range of noise exposure levels over which the confidence intervals intersect for percent highly annoyed by the total range of noise exposure levels common to two survey sites. A simulation study found that at least 11% of the noise exposure level range should overlap for the data between two sites to be considered similar. The second tool is the intraclass correlation coefficient, or variance partition coefficient, which measures the proportion of variance attributable to difference between groups in hierarchical data. A value closer to 1 implies significant clustering, while a value closer to 0 implies that the data are more similar across survey sites. Finally, the third tool is a comparison of the proportion of highly annoyed responses at the highest noise exposure level bin across two or more survey sites using the Marascuillo procedure to compare all possible pairs of proportions.

The ultimate techniques for merging the data will depend on characteristics of the actual data collected, especially whether all, just a subset, or none of the data across sites are considered consistent enough to merge.

CONCLUSIONS

To collect nationally representative data on the human response to reduced sonic booms, NASA will conduct a campaign of X-59 community surveys at up to five sites in different geographic regions of the US. This paper summarizes some of the key methodological and experimental design decisions made to maximize the validity of the results. For the dose-response statistical model, several promising techniques have been identified, including multilevel logistic regression and a two-stage model. To minimize the potential for distortion in the dose-response curves, techniques such as structural Bayesian hierarchical models will be used to attempt to account for measurement error. A control condition is planned to assess baseline annoyance without any X-59 flights and help ensure valid inferences from the survey data. The survey data will be analyzed for evidence of carryover effects, even though it may not be possible to fully avoid these effects via experimental design. Finally, careful consideration will be given to the question of if and how data from multiple survey sites are combined into a single, representative dose-response relationship.

Acknowledgements
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Residential greenery affects noise annoyance depending on transport source and region

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ABSTRACT

Residential greenery has received much attention in recent years as a measure to reduce negative health effects of transportation noise. To elucidate its association with transportation noise annoyance, data sets of three large field surveys were recently analyzed with the green metric NDVI (besides other metrics, depending on the study): the Swiss nation-wide surveys SiRENE (road, rail, air) and RESTORE (road), and the large-scale German NORAH study (road, rail, air) covering four major German airport regions. The analyses revealed that residential greenery was associated with reduced road traffic noise annoyance, but with increased aircraft noise annoyance, while only a weak or no consistent association at all was found for railway noise annoyance. Further, while residential greenery in the Swiss studies was found to be an "additive" predictor for annoyance, besides noise exposure (day-evening-night-level L_{den}), it was a moderator in the German study, i.e., its effect depended on the L_{den}. Literature often euphorically emphasized the beneficial role of residential greenery regarding adverse noise effects. While residential greenery should without doubt be fostered, our analyses show that the association between noise annoyance and residential greenery is complex and depends on the noise source and study region (or environmental context).

INTRODUCTION

Residential greenery has received much attention in recent years as a measure to reduce negative health effects of transportation noise. To elucidate its association with transportation noise annoyance, data sets of three surveys were recently analyzed: the Swiss surveys SiRENE [5] and RESTORE [3], and German NORAH study [4]. While some insights of the three studies are in line, others seem somewhat contradictory. In this paper, we compare the results of the three studies regarding the link of transportation noise annoyance to residential greenery. First, we give a short overview of the studies. Then, we present their main insights including which aspects seem in line and which to disagree. Finally, we present results of additional analyses to shed more light on potential differences between study regions regarding the association of noise annoyance with residential greenery.

METHODS

Study overview

Data sets: This contribution discusses the Swiss nation-wide surveys SiRENE [5] and RESTORE [3], and the large-scale German NORAH study covering four major German airport regions [4]. The main common objective of the three studies was to investigate the association of annoyance with residential greenery over a wide transportation noise exposure range. The two studies [4] and [5] constituted re-analyses of existing data sets (SiRENE: [1]; NORAH: [6]) after being complemented with green metrics, while the RESTORE data sets had been collected with the explicit aim to study the link of noise annoyance to greenery. SiRENE and NORAH cover the three sources road traffic, railway and aircraft noise in different airport regions (SiRENE: Basel [BSL], Geneva [GVA], Payerne [PAY], Zurich [ZRH]; NORAH: Berlin-Brandenburg [BER], Cologne/Bonn [CGN] Frankfurt [FRA], and Stuttgart [STR]). RESTORE only covers road traffic noise but comprises two separate surveys: a Swiss-wide survey (CH) and a survey covering the city of Zurich (ZH). Table 1 gives an overview including the number of collected annoyance ratings.

Noise annoyance: Following the recommendations of ISO/TS 15666 [2], we use the binary variable "highly annoyed (HA)" as a measure of noise annoyance. In SiRENE and RESTORE, HA is derived from the 11-point numerical scale, defined as 1 ("highly annoyed") for the top three numerical categories 8–10, and denoted as HA_N. In NORAH, HA it is derived from the 5-point verbal scale, defined as 1 ("highly annoyed") for the top two verbal response categories 4 ("very"), and 5 ("extremely") of the 5-point scale, and denoted as HA_V.

Exposure metrics: All three studies used the day-evening-night level (L_{den}) of the loudest façade as the noise exposure metric and the green metric "normalized difference vegetation index" NDVI [7] (besides other green metrics not discussed here).

Exposure response curves: Exposure-response curves (ERCs) were established by logistic regression analysis to model the association of the probability of HA (pHA) with different predictor variables. In the SiRENE analysis [5], the main model (denoted as Model 3) accounts for the source-specific (road, rail, air) dependence of pHA on L_{den}, NDVI, degree of urbanization (DEGURBA of the European statistical office Eurostat), an interaction of NDVI × degree of urbanization (i.e., the effect of NDVI may depend on degree of urbanization and *vice versa*), as well as personal characteristics. In the NORAH analysis [4], the model accounts for the source-specific (road, rail, air) dependence of pHA on L_{den}, airport region, NDVI and the interaction L_{den} × NDVI. Finally, the RESTORE analysis [3] accounts for the dependence of pHA (road) on L_{den} and NDVI, separately for the two surveys (CH and ZH). Only NORAH found a significant interaction L_{den} × NDVI (denoting that the effect of NDVI may depend on the level of L_{den} and *vice versa*), contrary to SiRENE and RESTORE, as discussed below.

Chronologically, the analysis of the SiRENE dataset was performed first, followed by the analyses of NORAH and then RESTORE. More details on the three studies are given in the respective publications [3-5].

Additional analyses

Driven by the insights of the NORAH study, we did two additional analyses of the SiRENE data set. First, we did an airport region specific analysis to see whether aircraft noise annoyance depends on environmental context. The model accounts for the dependence of pHA on L_{den}, airport region (BSL, GVA, PAY, ZRH) and NDVI as in NORAH [4], but without the interaction L_{den} × NDVI. The analysis is based on the following number of observations (total of N = 3'096): N = 348 (BSL), N = 772 (GVA), N = 29 (PAY) and N = 1947 (ZRH). (One of the 3'097 observations [Table 1] was excluded as it was not attributed to any of the four airport regions.) Due to the small number of observations, the PAY results are not presented.

Second, we tested the dependence of pHA (road, rail, air) on L_{den}, NDVI and the interaction of L_{den} × NDVI. No model adjustments with personal characteristics were performed here.

Table 1: Overview of the three studies on noise annoyance discussed in this contribution: country, noise sources, number of noise annoyance observations (N) per noise source (SiRENE, NORAH) or survey (RESTORE: Swiss-wide [CH], city of Zurich [ZH]), and airport regions covered

Study [Reference]	Country	Noise sources	N	Airport region
SiRENE [5]	Switzerland	Road, Rail, Air	Road: 5,431, Rail: 3,536, Air: 3,097	BSL, GVA, PAY, ZRH
RESTORE [3]	Switzerland	Road	CH: 2,229, ZH: 1,111	-
NORAH [4]	Germany	Road, Rail, Air	Road: 26,577, Rail: 26,574, Air: 26,601	BER, CGN, FRA, STR

RESULTS

Main insights of the three studies

The re-analysis of the SiRENE data set [5] revealed that residential greenery was associated with reduced road traffic and railway noise annoyance, but (strongly) increased aircraft noise annoyance. The effect may be quantified by a corresponding equivalent level change (ΔL) of the respective noise source. ΔL amounts to level reductions of ~6 dB and ~3 dB for road traffic and railway noise, respectively, but to a level increase of ~10 dB for aircraft noise, when residential greenery increases from “not much green” (5th percentile of the study sample distribution) to “much green” (95th percentile). The findings were similar for the RESTORE data set [3], with equivalent level reductions of ~4 dB in the CH sample and ~3 dB in the ZH sample. Here, the effect was more pronounced for whole Switzerland than in the urban context of Zurich. In the NORAH data set [4], residential greenery was found to moderate the association of annoyance with noise exposure. At low to medium exposure (up to ~60 dB L_{den}), road traffic noise annoyance decreased with increasing residential greenery, but increased at higher noise exposure. For aircraft noise, the opposite was found. Here, noise annoyance increased with increasing greenery up to ~55 dB L_{den} but decreased at higher noise exposure. For railway noise annoyance, no consistent trend was found. Pooled over the four airport regions, L_{den} increasing from 35 to 70 dB resulted in an equivalent level reduction of 8 dB to a level increase of 3 dB for road traffic, a level increase of 4 dB to a level decrease of 2 dB for railway, and a level increase of 2 dB to a level decrease of 1 dB for aircraft noise. Further, the results strongly depended on airport region.

Thus, taken together, the three studies suggest the following: First, while residential greenery generally seems to positively affect (i.e., reduce) road traffic noise annoyance, aircraft noise annoyance seems to increase with increasing residential greenery. Second, for railway noise, no consistent association may be reported (also in the Swiss SiRENE study, this association was weakest), indicating that other factors, not covered by a metric merely quantifying green, might play a role. Third, depending on the study region/context, residential greenery may act as a moderator (NORAH) or as a mere "additive" predictor (SiRENE, RESTORE). Finally, the effect of residential greenery may depend on the airport region, showing that environmental context may crucially affect the effect of residential greenery on noise annoyance. The latter two points are elucidated in the following additional re-analysis of the Swiss SiRENE study.

Environmental context (airport region) in Switzerland

Figure 1 shows the dependence of pHA_N on aircraft noise exposure and residential greenery, separately for the three airport regions BSL, GVA and ZRH. No interaction term L_{den} × NDVI was added to the ERC, as this term was found to be non-significant ($p > .58$). While the curves are highly disparate between the three airport regions, pHA_N consistently increases with increasing greenery in all three airport regions (as well as in PAY, not shown), although to different degrees.

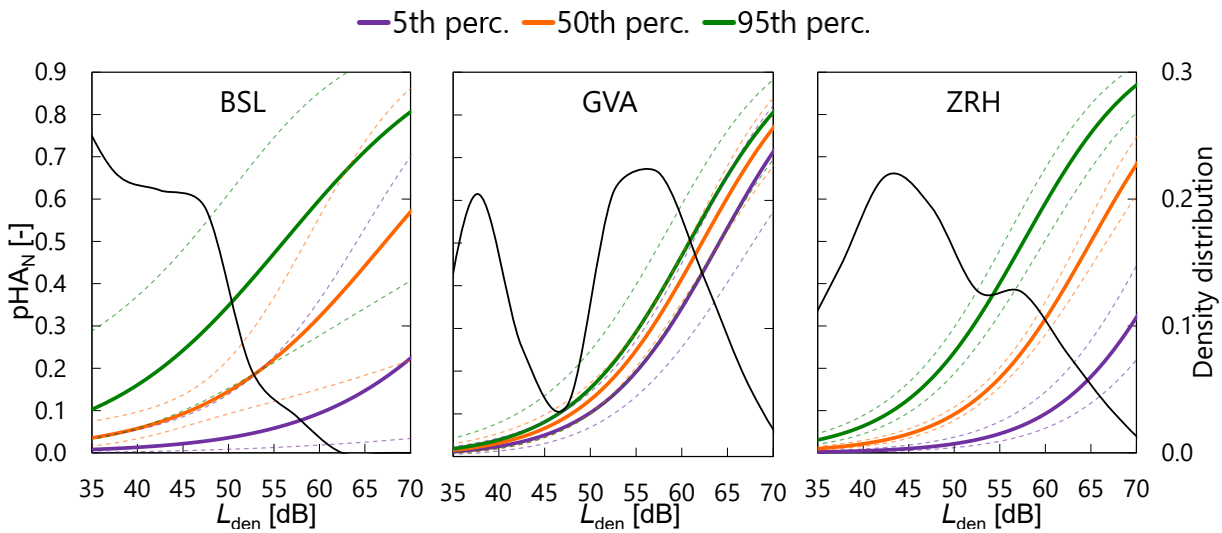

Figure 1: Exposure-response curves for pHA_N of the SiRENE survey as a function the L_{den} and NDVI for aircraft noise, including 95% CI, and density distribution of observations (secondary axis), separately for the three airport regions BSL (left), GVA (middle) and ZRH (right). The three exposure-response curves per plot represent the 5th, 50th and 95th NDVI percentiles (overall values of the Swiss sample: NDVI = 0.33, NDVI = 0.55 and NDVI = 0.72, respectively [5]).

Residential greenery as a moderator: what about SiRENE?

Confirming the previous findings of [5] but contrasting those of NORAH [4], the re-analysis of the SiRENE data set with the interaction term L_{den} × NDVI showed that the interaction term is not significant for all three noise sources (road: $p = .131$; rail: $p = .667$; air: trend, $p = .052$). Accordingly, Figure 2 shows that also with the (non-significant) interaction term L_{den} × NDVI, no apparent dependence of the effect of NDVI on the level of L_{den} or *vice versa* is visible.

Further, for railway noise the effect of residential greenery is non-significant ($p > .49$). This is in line with the findings from NORAH [4] insofar es the latter study found the ERCs of railway noise to be very disparate between airport regions and thus the association of noise annoyance with greenery to be rather inconclusive. (Note that in the original analysis of the SiRENE survey [5], a significant effect of NDVI was found, but only if personal characteristics were included in the analysis.)

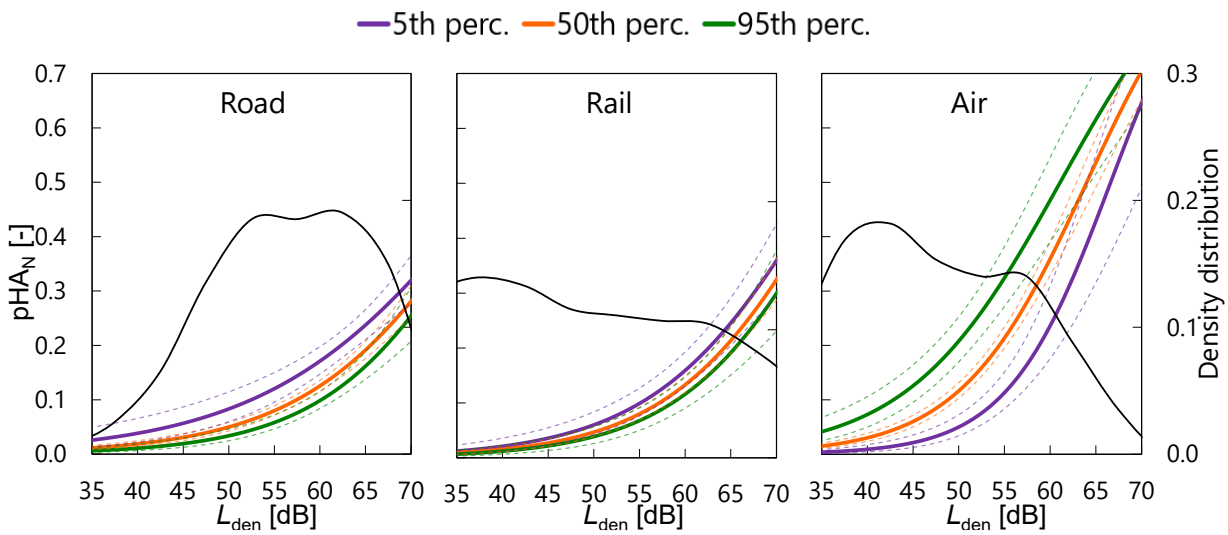

Figure 2: Exposure-response curves for pHA_N of the SiRENE survey as a function the L_{den} and NDVI for road traffic (left), railway (middle) and aircraft noise (right), including 95% CI, and density distribution of observations (secondary axis). The three exposure-response curves per plot represent the 5th, 50th and 95th NDVI percentiles (overall values of the Swiss sample: NDVI = 0.33, NDVI = 0.55 and NDVI = 0.72, respectively [5]).

DISCUSSION AND CONCLUSIONS

In this contribution, we compared results from three field studies on the effects of residential greenery on transportation noise annoyance. The studies consistently report that greenery reduces road traffic noise annoyance (equivalent level reduction of 3—6 dB in the Swiss studies; level-dependent reduction up to an L_{den} of ~60 dB in the German study), while aircraft noise annoyance increases with increasing greenery (equivalent level reduction of ~10 dB in the Swiss study; level-dependent increase up to an L_{den} of ~55 dB in the German study). For railway noise, the results are only weak (Swiss study: equivalent level reduction of ~3 dB) and somewhat inconsistent (German study). Possible reasons for this disparate “greenery effect” between transportation noise sources have been discussed in the respective publications [3-5]. Besides the dependence of the noise source, the “greenery effect” also strongly depends on the study region: the effect size was found to be different for whole Switzerland compared to the city of Zurich (road) [3], and also between airport regions (air; German and Swiss airport regions). Finally, residential greenery can either act as an additive predictor (Switzerland) or a moderator (Germany). The effects of greenery thus strongly depend on environmental context and airport region, highlighting the importance of local conditions.

Overall, the studies emphasize that the “greenery effect” (i) goes beyond a mere reduction of noise exposure in greener areas, but is attributed to the vegetation and green environment, and (ii) is not generalizable irrespective of the individual exposure situation. Rather, regional differences may play an important role, but potentially important factors and their exact role are still poorly understood.

In conclusion, while residential greenery should without doubt be fostered, our analyses show that the association between noise annoyance and residential greenery is complex and depends on the noise source and study region (or environmental context).

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Annoyance caused by exposure to environmental noise Quantifying the influence of non-acoustic factors

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ABSTRACT

The annoyance caused by exposure to environmental noises is only partly determined by the accumulated noise level such as DENL (or DNL). A number of other factors may also affect the annoyance response. The standardized CTL method for establishing exposure-response functions is ideal for quantifying the effect of all non-DENL factors (commonly referred to as "non-acoustic" factors). A case study on how residential greenery modifies annoyance from road traffic noise has been presented.

INTRODUCTION

In 1992 the US Federal Interagency Committee on Noise, FICON, declared that for annoyance purposes the noise exposure should be described by the equivalent level (or similar like DNL) and their favored measure for impact was "percent of the area population that was highly annoyed" [1]. This has become a *de facto* way of presenting the results from social surveys on noise annoyance. The responses are typically sorted in exposure bins, two to five dB wide, and the percentage of respondents reporting high annoyance is calculated for each bin. These results are plotted in a diagram showing prevalence of high annoyance versus the long-term average noise exposure level.

The international standard ISO 1996-1:2016 suggests two methods for establishing an exposure-response function, ERFs, based on such survey data. The methods are described in informative annexes E and F [2] . One may use regression, a purely mathematical approach which has no physiological or psychological interpretation, or alternatively use a method based on the Community Tolerance Level concept, CTL. The CTL method assumes that the annoyance increases with the noise level as does the duration adjusted loudness function. Thus, all ERFs have the same "shape" but the onset of the annoyance, that is the position of the response function relative to the noise axis, is determined by the effect of other, so-called non-acoustic factors. A complete ERF for a certain noise situation can be represented by a single value indicating the curve's position relative to the x-axis. By convention the exposure level corresponding to 50 % prevalence of high annoyance, the CTL value, is used as a

reference. Different noise situations can be compared with respect to annoyance, by comparing their CTL values, and the differences may be easily quantified. The difference between two CTL values tells how many decibels the noise in one situation must be increased or decreased in order for the two situations to be judged equally annoying. The CTL method is therefore ideal for studying how the annoyance response is affected by different outside factors.

In this paper the results from two Swiss studies on road traffic noise annoyance are analyzed with respect to the amount of greenery at the respondent's residence. The data for this analysis was supplied as supplementary data in the publication: Kawai et al. «Urban noise vs. nature's calm: A Swiss study of noise annoyance and the role of residential green» [3].

DATA MATERIAL

Data from two large surveys in Switzerland was presented in the paper by Kawai et al. One survey was a nationwide survey across Switzerland and the other focused on the city of Zurich. One of the aims of the surveys was to determine how residential green would modify the annoyance caused by road traffic noise. The amount of greenery around each respondent's residence was characterized using the Normalized Difference Vegetation Index, NDVI. The value of this index ranges from -1 to 1, where negative values indicate water, values around zero represent barren areas, sand or snow, 0.2–0.3 shrub and grassland, and values of >0.3 stand for increasing green. The long-term average noise level caused by road traffic was calculated at each residence. Potential respondents were contacted by regular mail and were provided with an individual access code to an online questionnaire. The annoyance was scored on a numerical 11-point scale. A detailed description of the surveys, selection methods, response rates, questionnaires, etc. can be found in [3].

For the present analysis we had 2230 valid responses from the nationwide survey and 1112 valid surveys from Zurich. The two datasets have been denoted CH (Switzerland survey) and ZH (Zurich survey) respectively.

OVERALL RESPONSE

Traditionally data from similar surveys have been combined to generate an overall exposure-response curve. For this purpose, the individual responses were sorted in 5 dB bins, and the prevalence of high annoyance was calculated for each bin. An ERF can thus be derived either by standard regression or by using the CTL method. The two methods yield very similar results as shown in Figure 1. Both functions have an equally good fit with r^2 (coefficient of determination) 0.95.

The commonly used limit at 10 % highly annoyed is found for DENL 52.5 dB (regression) and DENL 51.6 dB (CTL). It should be noted that these values cannot be directly compared with the limit values recommended by, for instance, WHO, as the survey methods are different (written response vs. interview).

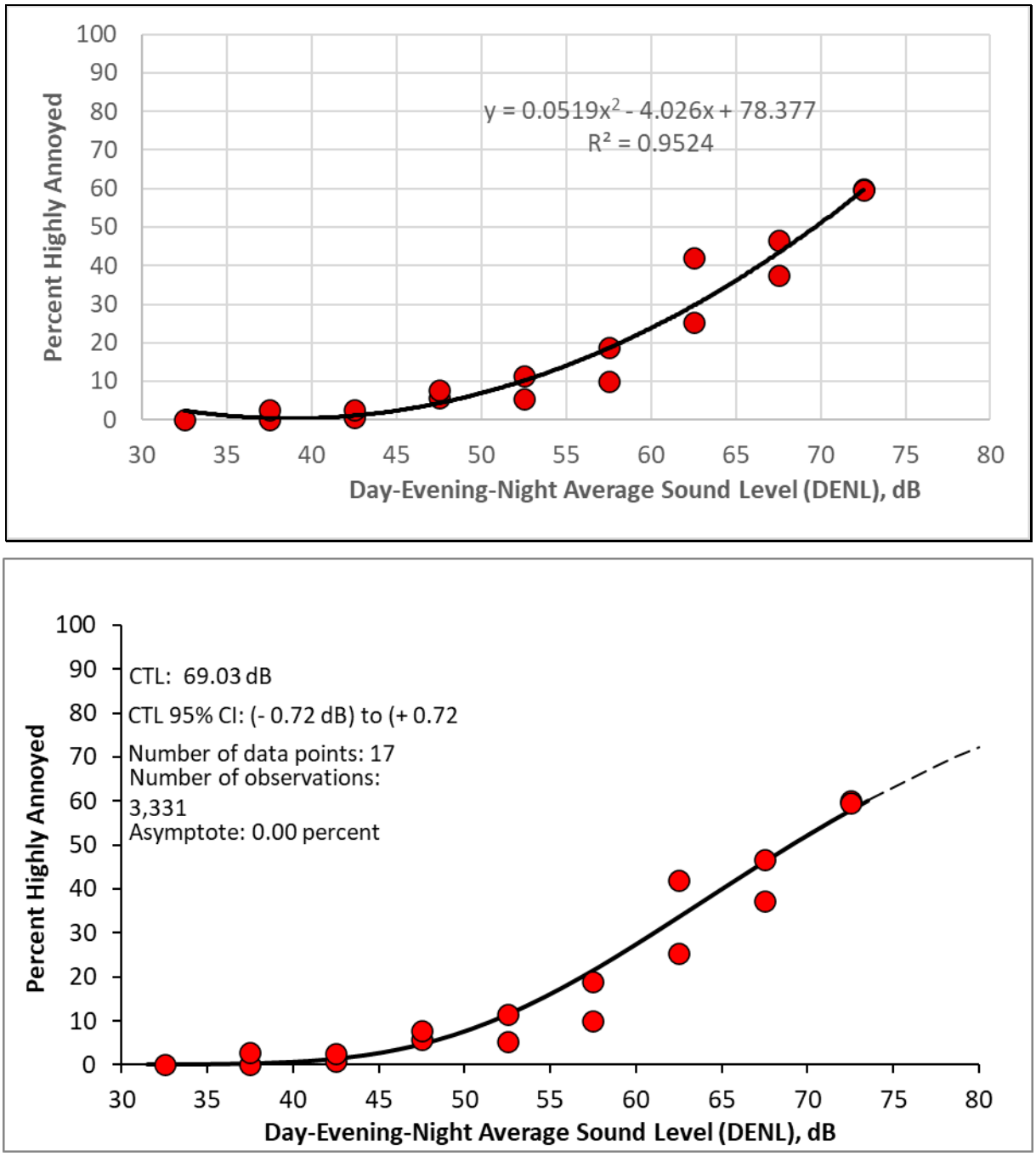


Figure 1: Exposure-response curves for combined Swiss survey results. The curves show prevalence of high annoyance with road traffic noise as a function of DENL.
Top panel: 2nd order polynomial regression, bottom panel: CTL method

THE EFFECT OF GREENERY

The annoyance response is not only affected by the noise level, but also a number of other factors [4]. The objective of the present analysis is to find out how the amount of greenery at the respondent's residence affects the response.

A standard survey will always show the combined effect of all non-DENL factors, and it is very difficult to isolate the effect of a single one. Results from different surveys cannot be combined for the purpose of studying the effect of a special factor unless the prevalence of that factor is somewhat similar in the different surveys.

Figure 2 shows a scatterplot of the noise level and the greenery index for the CH study (nationwide) green dots and the ZH study (Zurich) red circles.

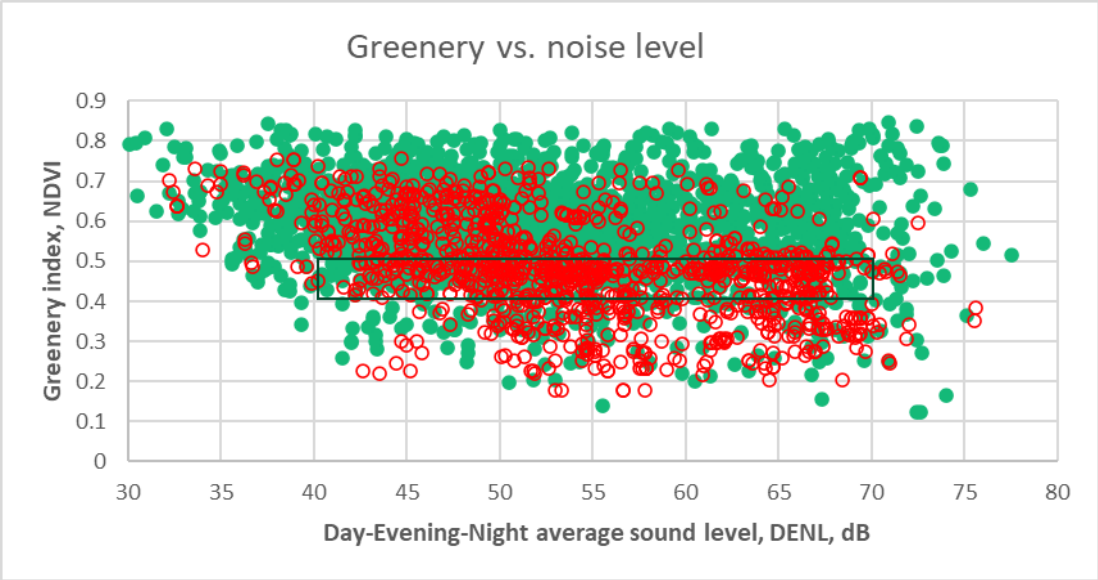
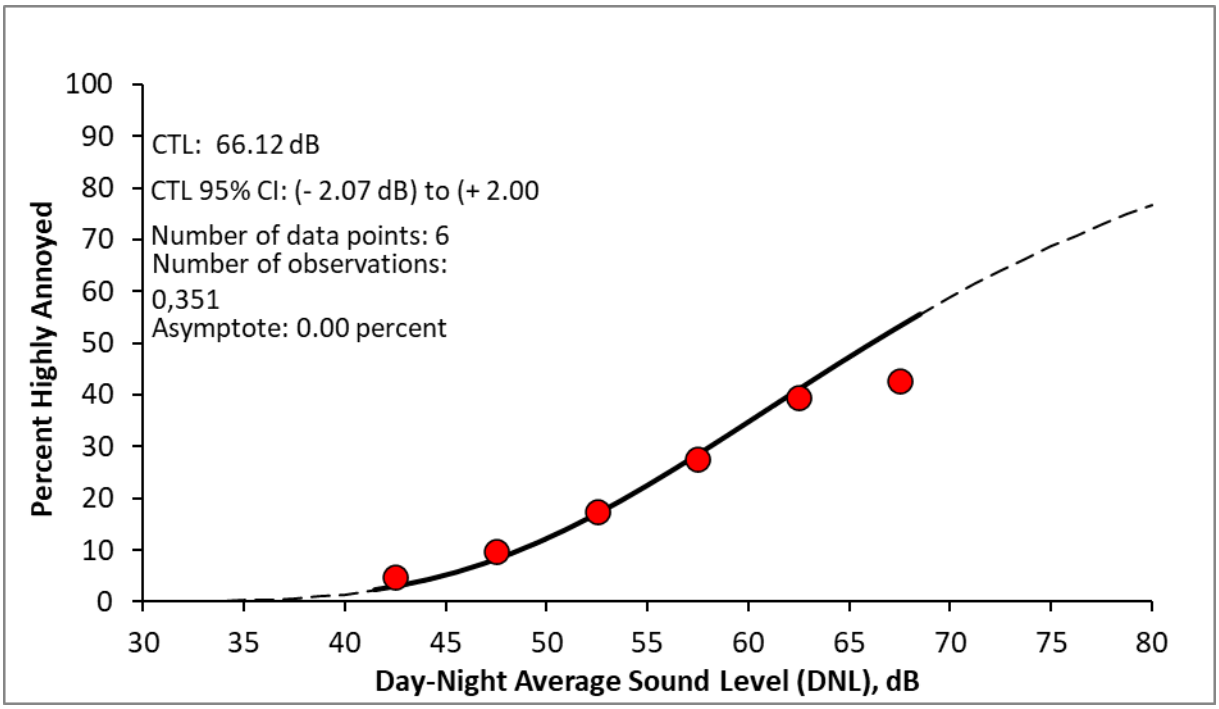


Figure 2: Scatterplot of greenery index vs. noise level for all respondents in the CH study (green dots) and the ZH study (red circles).

The figure shows that a sub-sample of respondents having a greenery index 0.4<NDVI<0.5 and a noise level 40 dB < DENL < 70 dB seems to have a somewhat similar prevalence of greenery for the two studies, CH: mean NDVI = 0.461, ZH: mean NDVI = 0.459 (marked by a rectangle in Figure 2).

A CTL analysis was conducted for the two sub-samples. The results are shown in Figure 3. The difference between the CTL values is Δ CTL = 6.1 dB, indicating that the ZH respondents are less annoyed than the CH respondents. They seem to tolerate 6.1 dB more noise for a given prevalence of annoyance. Since the amount of greenery is similar for the two samples, the difference in the annoyance response must be caused by other unknown factors.

The results from the two surveys can be combined for the purpose of studying the effect of a special factor, only if the effect of the other unknown factors is eliminated. If the CH data is used as a reference for a greenery analysis, this dataset can be supplemented with the ZH results by adjusting the ZH noise levels with the found Δ CTL = 6.1 dB.



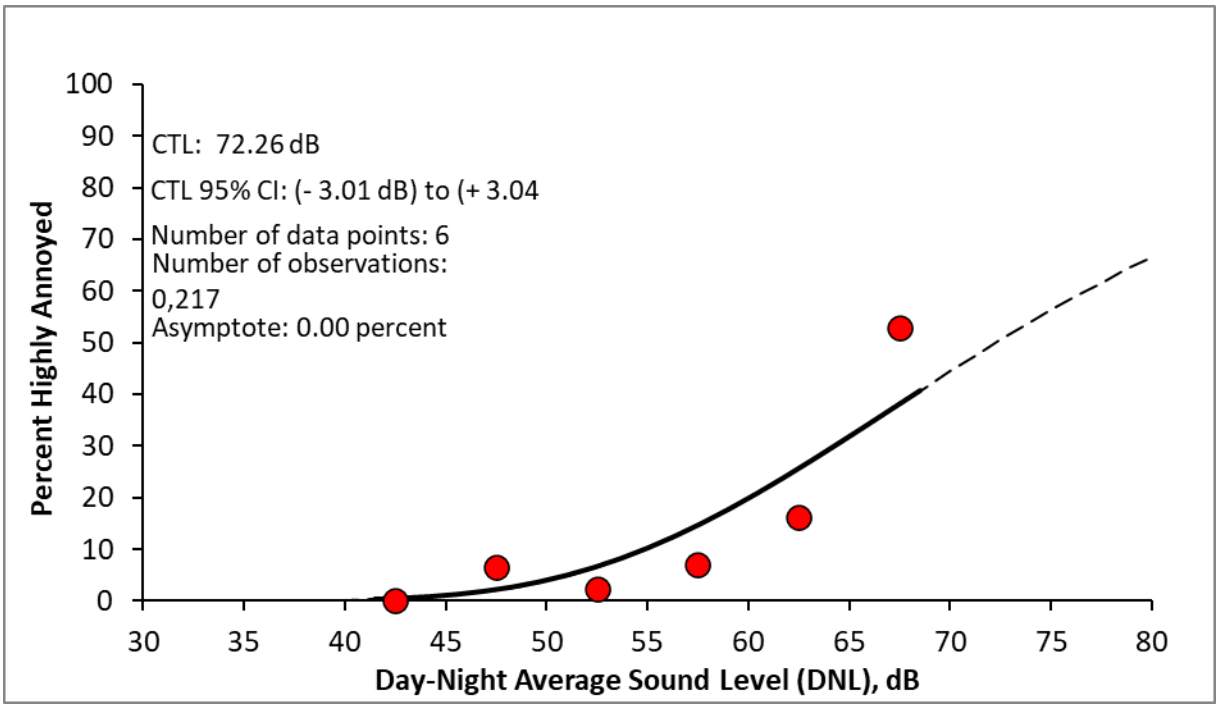


Figure 3: CTL analysis of two sub-samples of respondents having a greenery index 0.4 < NDVI < 0.5 and noise levels 40 dB < DENL < 70 dB. Top: CH, bottom: ZH.

The combined, adjusted dataset is sorted in “greenery bins”, 0.2 <NDVI <0.3, 0.3 < NDVI < 0.4, etc. and a CTL analysis is conducted for each sub-group. The results are shown in Figures 4 – 12.

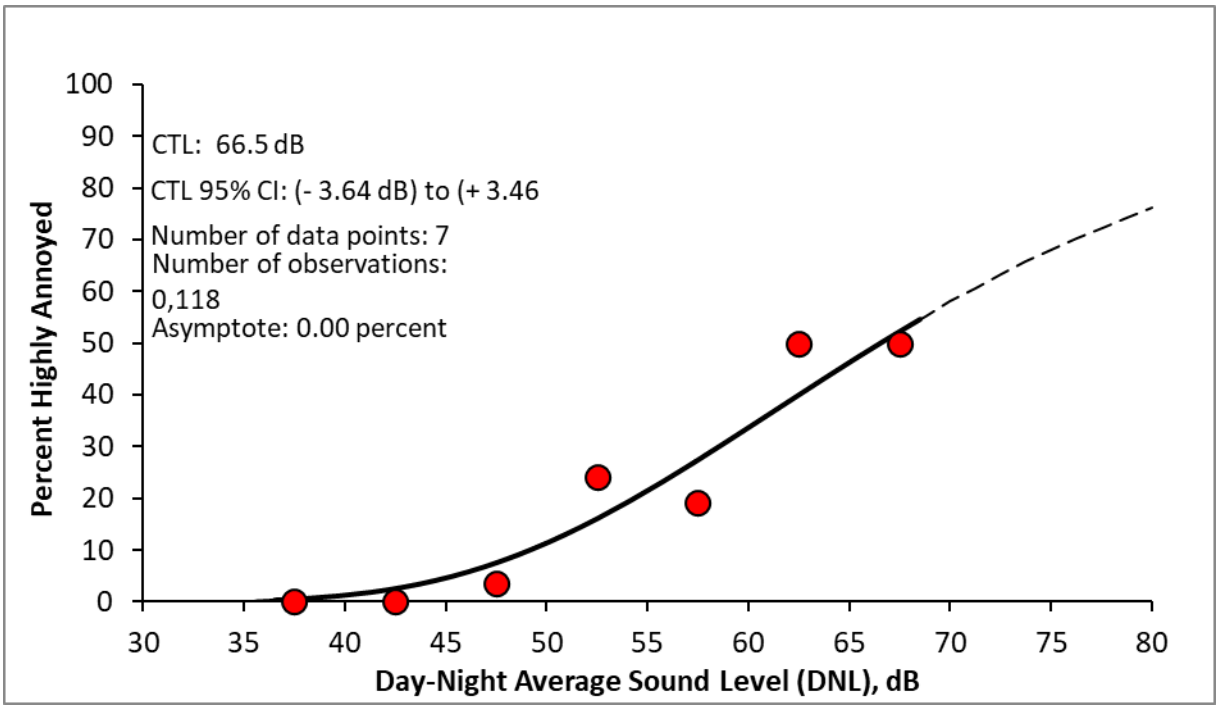


Figure 4: CTL analysis for residents with greenery index 0.2 < NDVI < 0.3

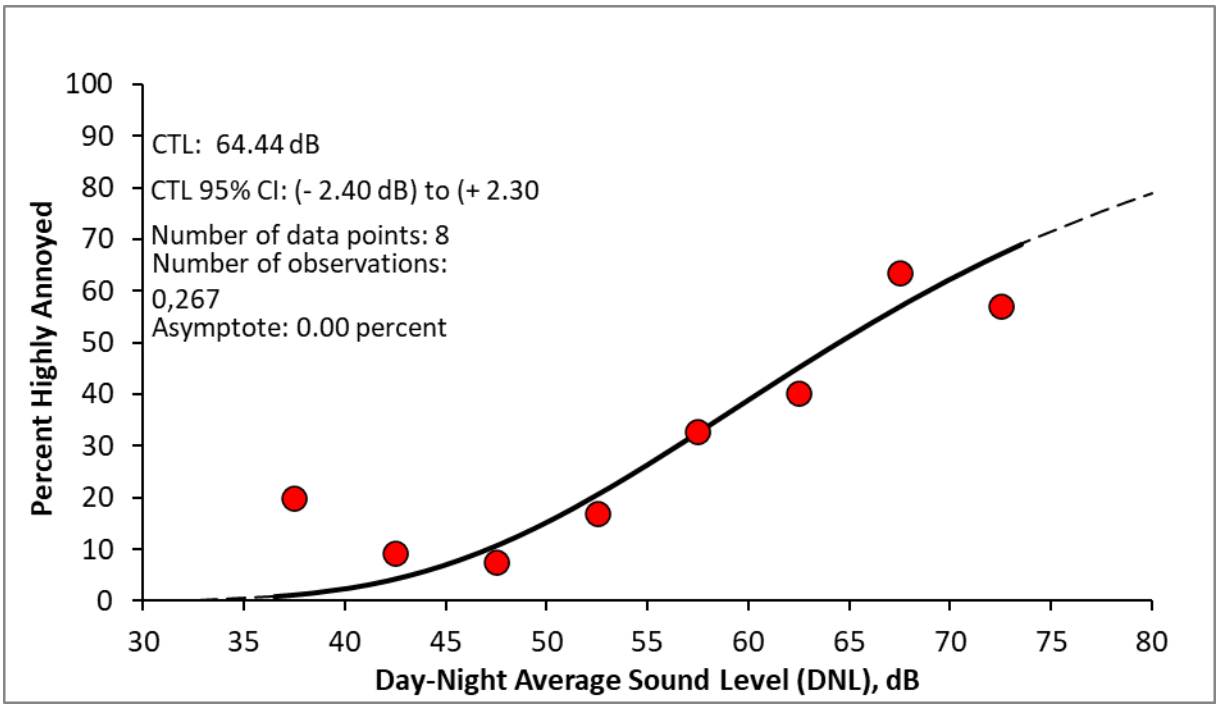


Figure 5: CTL analysis for residents with greenery index 0.3 < NDVI < 0.4

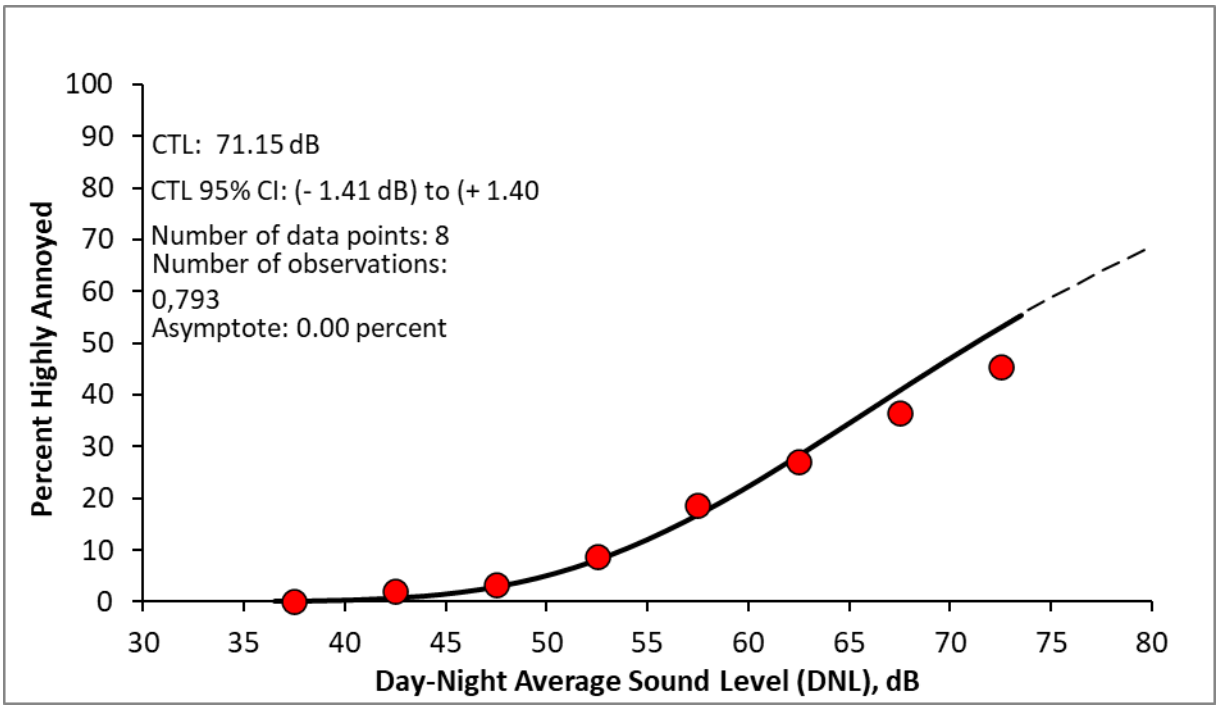


Figure 6: CTL analysis for residents with greenery index 0.4 < NDVI < 0.5

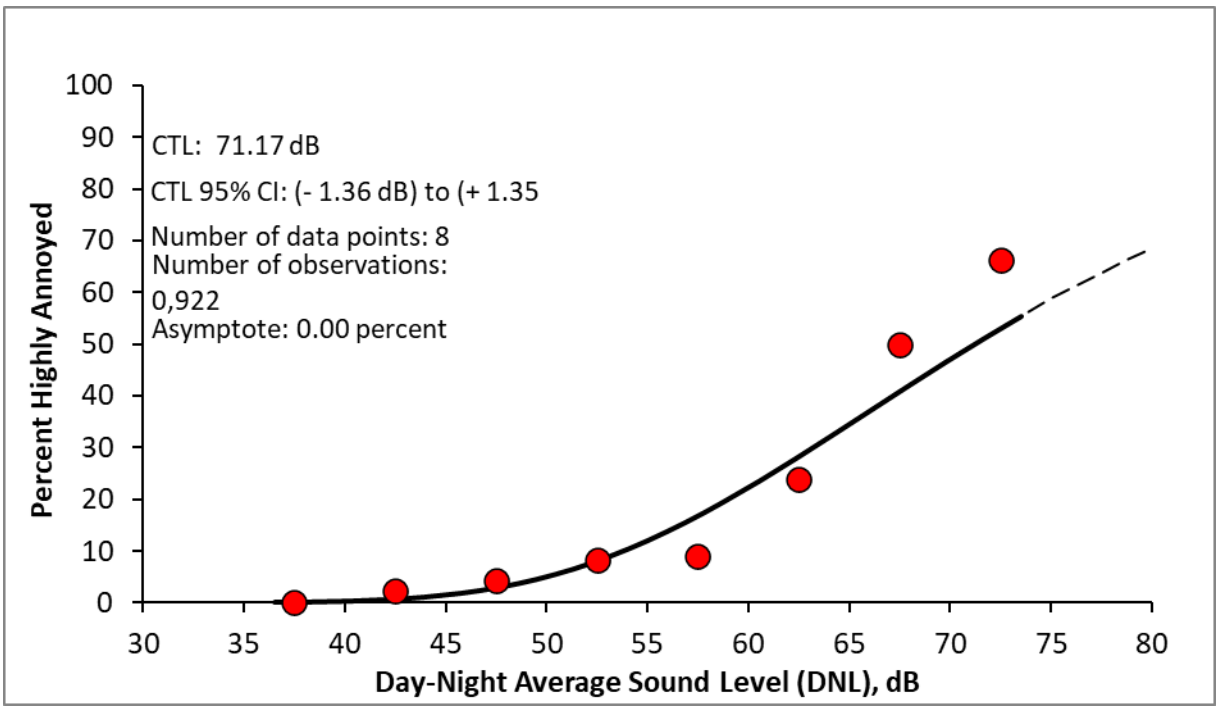


Figure 7: CTL analysis for residents with greenery index 0.5 < NDVI < 0.6

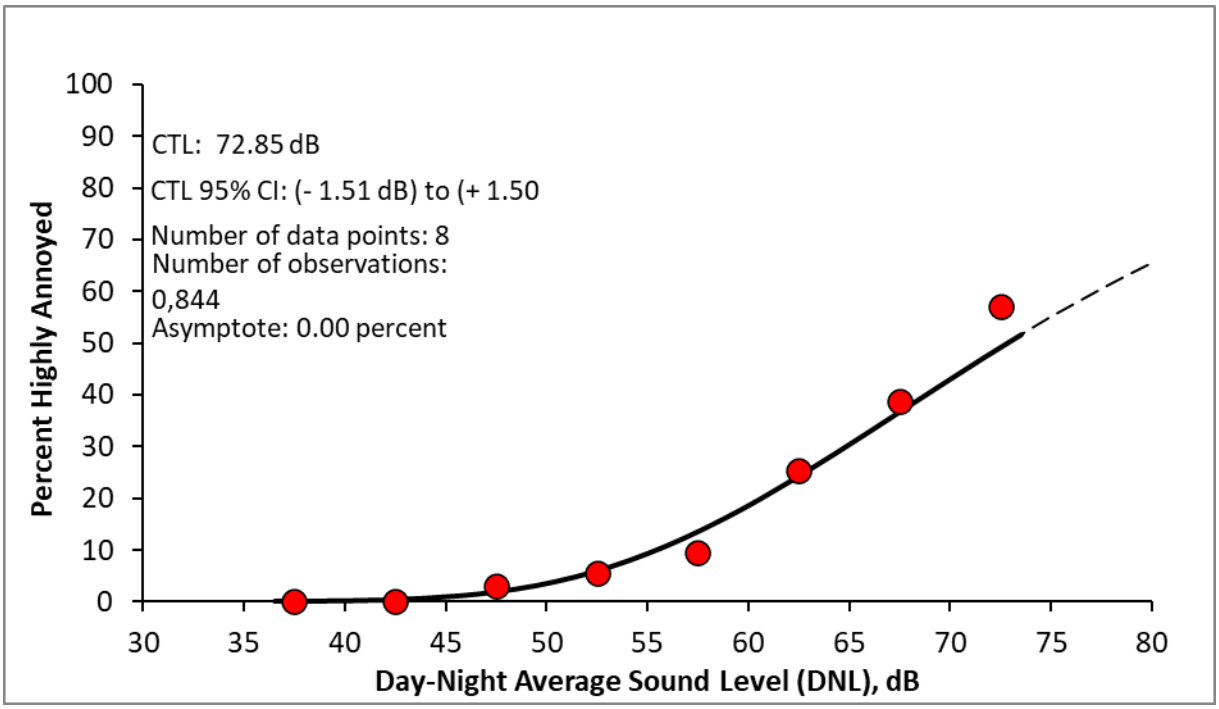


Figure 8: CTL analysis for residents with greenery index 0.6 < NDVI < 0.7

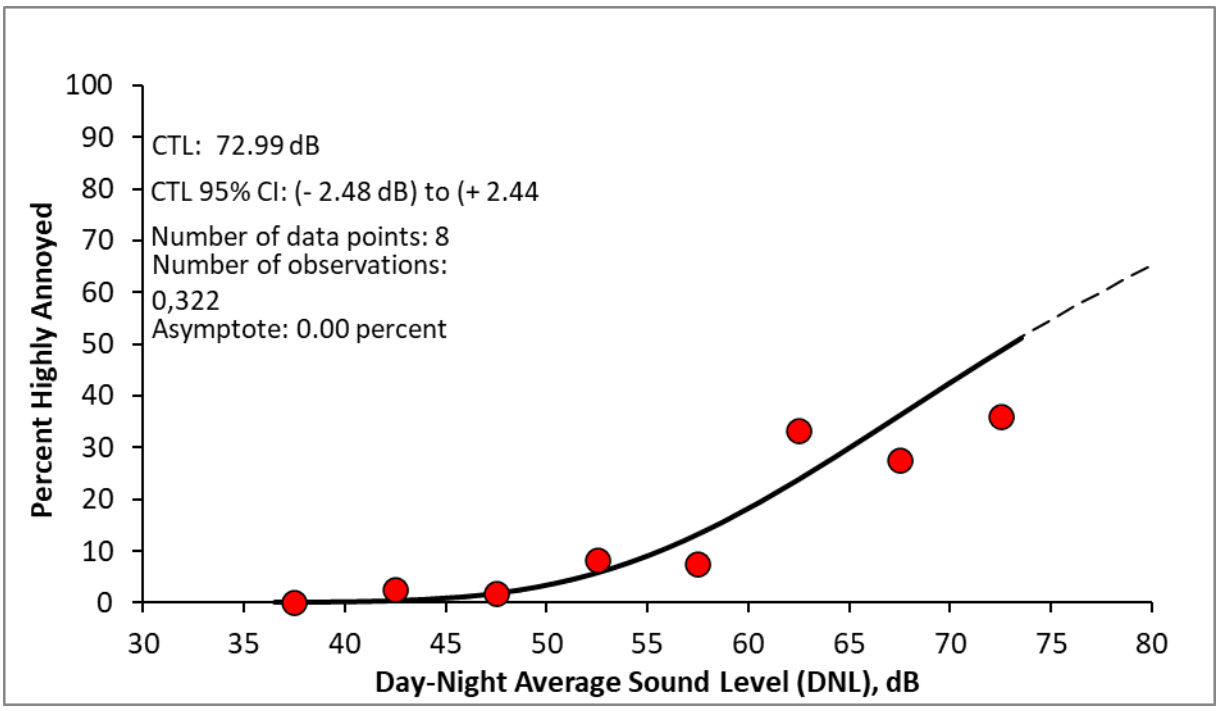


Figure 9: CTL analysis for residents with greenery index 0.7 < NDVI < 0.8

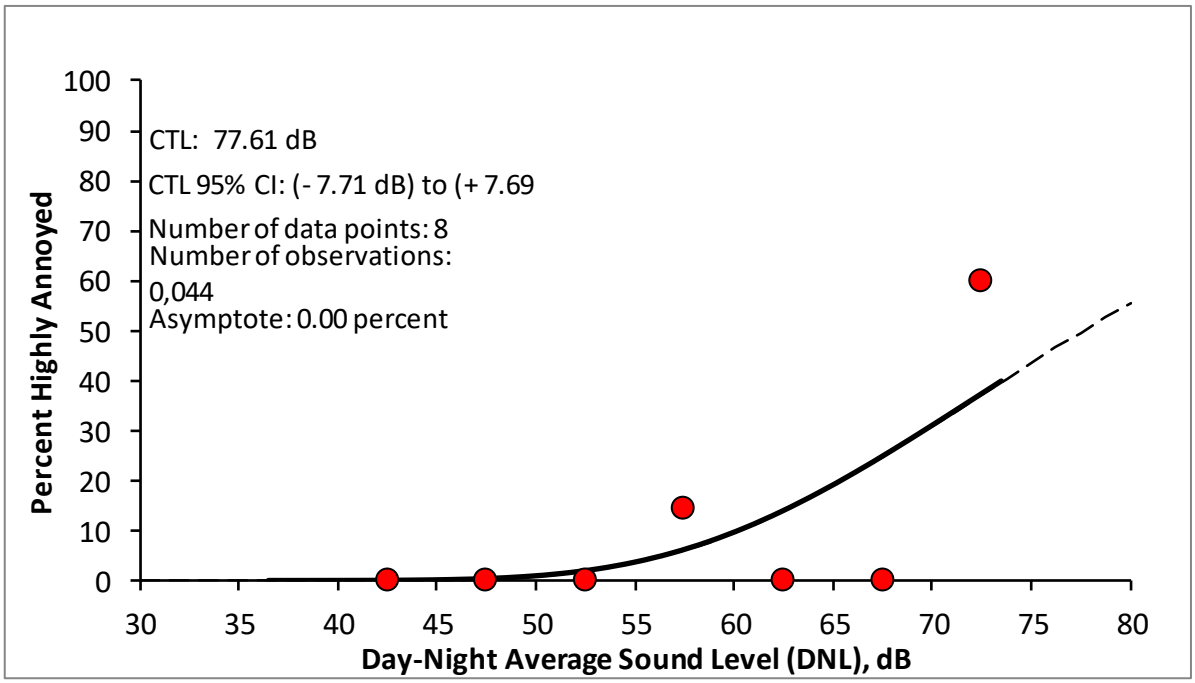


Figure 10:. CTL analysis for residents with greenery index 0.8 < NDVI < 0.9

The results from the CTL analyses can be combined as shown in Figure 11. A simple linear regression function has been fitted to the data. A statistical interpretation would be that the annoyance is modified by the amount of greenery at the respondent's residence. An increase in the greenery index Δ NDVI = 0.1 reduces the annoyance corresponding to a decrease of 1.9 dB in noise exposure.

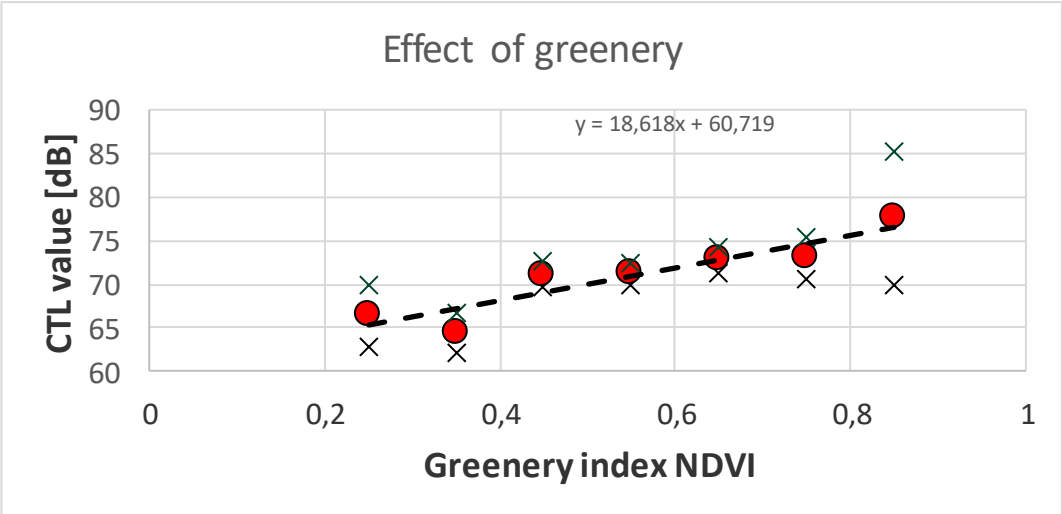


Figure 11: The relationship between greenery described by NDVI and annoyance described by the CTL value (x indicates 95% confidence). Higher CTL values mean less annoyance.

DISCUSSION AND CONCLUSION

The CTL method is a procedure for analyzing noise annoyance surveys for the purpose of constructing exposure-response functions. The basis for the method is the assumption that

the annoyance increases with the long-term noise level as does the loudness function. This assumption links the annoyance response to a physiological reaction whose validity can be experimentally tested. This is different from a method based on mathematical regression which does not attempt to “explain” the result other than as the outcome of a mathematical exercise.

Fidell et al. [5] and Schomer et al. [6] have applied the CTL method to a large number of existing surveys on transportation noise and have demonstrated its plausibility.

This paper demonstrates how the CTL method can be used to quantify the effect on annoyance by factors other than the long-term noise level. Figure 11 clearly shows that the amount of greenery at the respondent’s residence has a significant impact on the annoyance response. The linear regression function (dashed line) that shows the relationship between the greenery index and the annoyance, however, is merely a statistical exercise that cannot be readily verified. Another plausible explanation could be that the annoyance response is only affected by the neighborhood greenery at very low and very high values of the greenery index. For intermediate values (in the present case 0.4 < NDVI < 0.8) the annoyance response remains stable (the CTL value is constant). Which one of these interpretations that is more “correct”, cannot be proven experimentally, but analyses of multiple surveys may point to the likelihood of one or the other.

The CTL method simplifies the comparison of annoyance in different exposure situations and offers a readily comprehensible quantification of observed differences.

Acknowledgements

The authors appreciate that data from the Swiss studies [3] have been made available for open access via https://doi. org/10.5281/zenodo.14142439.

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Results obtained from low frequency noise research, and psychological approaches obtained from counseling of noise and low frequency noise complainants, and strategies for solving complaints

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ABSTRACT

This paper describes the findings obtained from fifty years of interactions with complainants. The exact number of consultation cases is unclear, but it is approximately 200 to 300 cases. The papers describing the complaint contents amounted to about two meters in thickness. When receiving complaints by telephone, the process proceeds through counseling techniques: attentive listening, attitude empathy, and building a relationship of trust. In the stage of attentive listening, the complainant's statements that they are suffering from noise or low-frequency noise are listened to carefully. During attentive listening, we give sufficient supports and conveys empathy regarding their distress. Through this process, a relationship of trust is built. Once a relationship is established, the complainant becomes prepared to accept the scientific explanations provided by us. The content heard is compared with scientific facts, and while considering the complainant's emotions, the discussion is gradually advanced. As scientific facts, it is noted that the hearing thresholds of complainants are not particularly low. When they perceive the sound, their response is strong. When the operating time of the sound source corresponds to the time of discomfort, the sound source is the real cause and problem is often resolved. When the times do not correspond, the machine is not the cause, the problem is difficult to resolve. Authors spend much time to maintain the relationship of trust as much as possible, with scientific thinking, and searching for a path to solve total psychological complainant's problem. The important role of local governments with complainants is also indicated.

INTRODUCTION

The author's long experience in providing consultation to complainants is considered useful for many complainants, municipal officials, researchers, and others in solving problems. Although the exact number is unknown, the author did consultations from approximately 200 to 300 people over fifty years. Some people wrote their symptoms every day and provided three years' worth of materials. The number of papers, including on-site survey results and complaint consultation contents, amounted to about ten thousand sheets, with a thickness of

about two meters. Although these were valuable materials, they were essentially privacy itself, and most of them were burned when I retired.

The symptoms reported were diverse, such as heart palpitations, difficulty breathing, and persistent unpleasant sensations. The symptoms were widely varied, and there were not special symptoms specific to the effects of low-frequency noise or noise. The most were considered stress reactions arising from unpleasant sensations.

In on-site surveys, the author always paid attention to confirming the correspondence between the operating condition of the sound source and the discomfort. If the operating time of the sound source and the time of discomfort were the same, it was judged that the sound source was causing the discomfort. However, to avoid psychological effects caused by seeing the sound source, the complainant was asked to judge the discomfort at a place where the sound source could not be seen and at the place, they felt most unpleasant.

Measurements of noise including low-frequency noise were conducted, and through conversations with complainants, the author attempted to estimate their psychological state and understood the phenomena, which they perceived as unpleasant.

The presence or absence of correspondence between the temporal changes of sound source operation and discomfort is important for determining the cause, but even without correspondence, it was certain that the person was annoyed by something.

The author also provided many academic and daily-life consultations to university students. The author was certified as a counselor by the Japanese Association of Counseling Science. Using knowledge of psychological counseling, the author observed the minds of complainants and searched for paths leading to solutions.

METHODS OF PSYCHOLOGICAL COUNSELING OBTAINED THROUGH COMPLAINT CONSULTATIONS

Entrance to Complaint Consultation

(1) Complainants who asked telephone consultations through the author's university.

(2) Complainants who became involved through media reports and through the process of conducting on-site investigations.

(3) Complainants related to the "NPO Association for Considering Noise, Vibration, and Low-Frequency Noise in Residential Environments."

(4) Complainants who were through researchers, municipal officials, acquaintances, and others.

Almost all complaints were accepted, listened to, and consulted on.

Attitude of Attentive Listening

At the starting point of consultation, the author paid attention not to deny what the complainant said at the beginning. Since the fact that they are annoyed is true, the attitude is to respect the other person and listen. In the field of counseling, this is called "attentive listening," meaning to listen carefully and stay close to the other person. When causal relationships were unclear, the author paid particular attention to listening.

Attitude of Empathy

The author listened to complaints for about 30 minutes to one hour. At the beginning, the author gives backchannel response. Regarding what the complainant is annoyed by, the author gives firm responses and conveys sufficient positive empathy. For non-scientific parts, the author responds in a weaker manner. Sometimes a little scientific explanation is added, but if it is not understood, the author does not force it.

A high-pitched voice or a hoarse voice is a sign of tension. When the voice frequency becomes lower and the speaking pace becomes slower, it is evidence that the person has calmed down. At first, the author matches the complainant's pace and speaks somewhat quickly, then intentionally slows down the speaking speed. When the complainant's speaking speed becomes slower, it indicates that tension is being released.

Building Relationship of Trust

When the attitude of empathy is conveyed to the complainant, a situation arises in which the complainant trusts the author. Once a relationship of trust is built, the complainant listens to what the author says. To bring the complainant closer to scientific thinking, the author sometimes gives suggestions to provide a certain direction.

If the direction of countermeasures becomes visible quickly, that is good, but in many cases, it takes much time. The author suggests immediate measures to make the complainant feel better, such as doing light exercises like stretching before going to bed, playing music or radio, or allowing some natural outdoor sounds in cases of low-frequency noise complaints. Scientific knowledge is also presented, but acceptance is not forced. When necessary, the author consults with the complainant about plans for on-site measurements.

At the end of the consultation, the author always says, "If you are annoyed or troubled, you may contact me anytime." By adding these words, both the complainant and the author can end the conversation with reassurance.

Points of Caution During Consultation

(1) When a relationship of trust is established, some problems can be solved by telephone alone.

(2) Even for complainants without correspondence between sound source operation and discomfort, the author does not cut them off. Since they are annoyed by something, it is necessary to identify the cause. If they can understand the cause of their own distress, they may accept it and move toward resolution on their own.

(3) There is some degree of risk in consultation activities. The author has changed mobile phone numbers to avoid some trouble between the author and the complainant.

(4) Even for complainants without correspondence, the fact is that they are troubled by some. Even when incorrect information from the internet is involved, once the complainant believes it, they can truly become unwell. While talking, the author analyzes the psychological aspects of why such beliefs arise.

(5) There are various states of human beings. Although the possibility is not high, it is necessary to know how to avoid suicide. When many symptoms such as difficulty falling asleep at night, waking up early in the morning, and loss of appetite appear, special attention is required. In noise complaints, the author meets a few complainants with schizophrenia. When a persecution complex is particularly strong, attention to suicide is necessary. The author contacts parents, public health centers, and physicians.

Difficulty of Scientific Understanding

Modern people live in artificial environments, so opportunities to experience actual phenomena directly have decreased. The body and mind become separated and it is difficult to make scientific thinking. Human relationships have become weaker. In cases of neighborhood noise complaints, people are not accustomed to resolving interpersonal relationships. Articles on the internet and smartphones are emphasized and it is difficult to judge correctness. Incorrect information causes suffering complainants. Complaints without correspondence have increased.

By having experience as much as possible, complainants can sense scientific facts.

It is important to open the experiential devices and low-frequency noise experimental equipment to complainants.

SEVERAL CASES OBTAINED THROUGH COMPLAINT CONSULTATIONS

(1) When there is correspondence between the operation of the sound source and the complaint, there is a countermeasure, so the issue is often resolved.

(2) Even when the noise level is below the regulatory standard of the Noise Regulation Law, complaints are frequent.

(3) In the case of a complainant suffering from low-frequency noise from an oil boiler, the author recommended engaging in volunteer activities and going outside during the daytime. Although the sound did not change, the complainant said that by going outside, the sound no longer bothered her.

(4) There was a case in which the problem was resolved through telephone consultation and by sending a measuring instrument to the complainant for self-measurement, and the complainant understood that there was no problem and understood their own situation.

(5) There were two cases in which the unpleasant sensation of low-frequency noise increased when the window was opened slightly. A standing wave phenomenon became strong indoors.

(6) In recent buildings, sound insulation is good, and in many cases, low-frequency noise cannot be perceived indoors when the windows are closed. When the interior is extremely quiet, sometimes tinnitus tends to occur.

(7) Indoors, noise or low-frequency noise may not be perceived, but near the sound source, the operation of the equipment can be recognized and cause an unpleasant sensation. The complainant then moves indoors while maintaining that unpleasant sensation, and it is assumed that complainant feel that the sound is heard indoors.

(8) The author sometimes asks complainants to perform self-analysis of their psychological state by distinguishing between physical phenomena, perceptual phenomena, and psychological reactions arising from those perceptions. However, scientific analysis is extremely difficult for complainants.

(9) Even family members living together sometimes find it difficult to understand the complainant’s statements, but because they are family, many take an attitude of agreeing with the complainant’s expressions. A confused atmosphere appears on the faces of family members.

(10) The way of the sound-source side responds is important. If the sound-source side listens to the complainant’s story well, the problem does not become complicated. A compromise point can be found.

SUMMARY OF EXPERIENCES TOWARD RESOLUTION

In cases where there is correspondence, the cause is clear, so in many cases the issue is resolved. Even when the cause is clear, if the noise level is below the regulatory standard, the issue may not be resolved due to the relationship with the cost of countermeasures.

There are sometimes requests from complainants who say they will pay the cost themselves and want the countermeasure implemented so that the problem can be resolved.

In cases without correspondence, resolution is extremely difficult. Even when it is possible to show that the issue is not a problem of noise or low-frequency noise, it is difficult to make the complainant accept this. This is an aspect in which the complainant denies their own existence. The phrase “because of low-frequency noise” becomes a kind of escape that serves as salvation for their sense of self.

EXPERIENCES WITH TWO COMPLAINANTS, WHO HAD EXTREMELY STRONG RESPONSE

In the cases of two complainants, there was correspondence between the operation of the sound source and the complaint. After telling them that they could stop at any time if they felt uncomfortable, the author began threshold measurements. During the measurement, this unpleasant sensation became extremely strong, and the measurement was stopped. When the volume was kept at a level of several decibels below the subject’s threshold, nothing happened, but when the level just exceeded the threshold, a strong feeling of anxiety occurred.

When an anxious emotion arises, the author first shows an attitude of supporting the anxiety. Using the method of association, the author says: “Low-frequency noise is unpleasant, isn’t it?” “Low-frequency noise also comes from cars, doesn’t it?” “When you ride in a car and go somewhere, it is enjoyable, isn’t it?” “There are many enjoyable things in life.”

The topic is gradually shifted to brighter subjects. After talking for about 15 to 30 minutes, the subject also calmed down.

MY EXPERIENCE AS A COMPLAINANT

When a three story apartment building was constructed in front of my house, a “boon” sound began to be heard. The sound from the cooling tower of a hotel located 130 meters away began to be heard as it was reflected by the apartment building. The noise level was 37 dB. For half a year, I wondered whether I should complain to the city’s pollution control section, request action from the neighborhood association president, or speak directly to the sound source side myself. In the end, I gathered my courage and spoke directly to the sound source side.

When I felt unpleasant about this sound, I thought, “This experience of a complaint is a good opportunity to experience the feelings of complainants.” As a result, my unpleasant feeling toward the sound decreased. This was due to a change in my interest of advantageous or disadvantageous in the sound. This is consistent with the fact that the amygdala in the limbic system of the brain feels comfort when the phenomenon occurring is advantageous to my survival, and feels discomfort when it is disadvantageous.

FACTS BASED ON SCIENTIFIC DATA

This chapter summarizes the scientific findings obtained through many years of research by the authors and colleagues. For the original papers, refer to the author's articles in the Journal of Low Frequency Noise and Vibration and Control in literature.

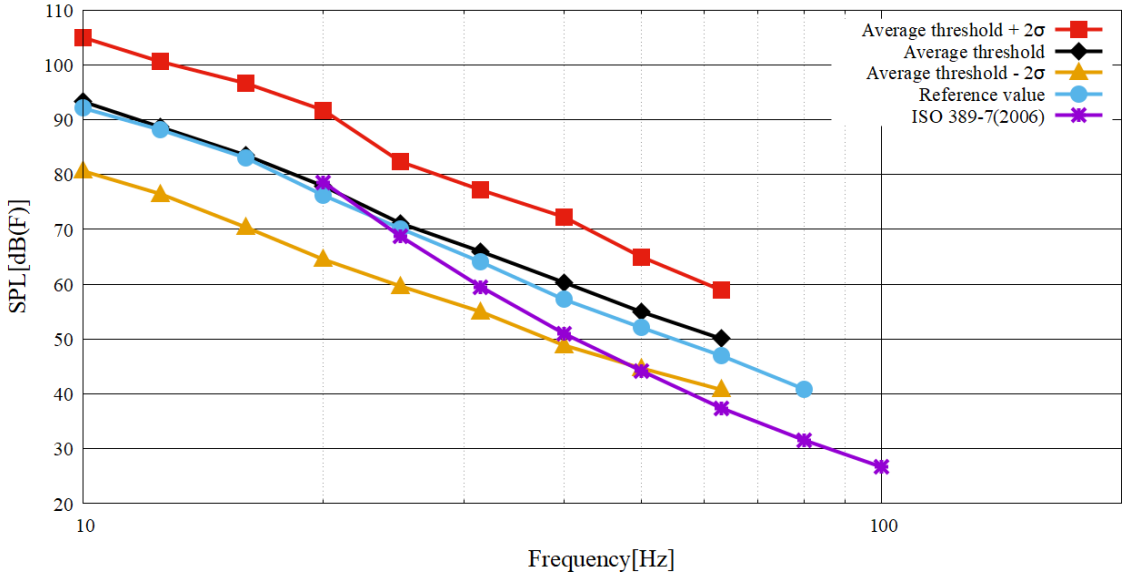

Figure 1 Threshold measured by up-down method of continuous sound

Fig.1 shows that the average threshold values (black line) measured by the up and down method using continuous sounds, which are common in actual environments, are higher than the thresholds measured by the ISO method using intermittent sounds (ISO 389 7). In addition, the Japanese reference values for low frequency noise (green line) are very close to the average threshold values for continuous sounds [4, 5] .

Table 1: Yatabe Guilford Personality Test of Low-Frequency Noise Complainants

A	0	B	1	C	0	D	1	E	0
A'	1	B'	1	C'	0	D'	4	E'	2
A"	0	AB	1	AC	0	AD	0	AE	1

A: average type, B: unstable proactive, C: stable passive, D: stable proactive, E: unstable passive

Table 1 shows that the personalities of the 12 complainants with correspondence show no particular characteristics, and there are not many personality differences compared with the general population [7].

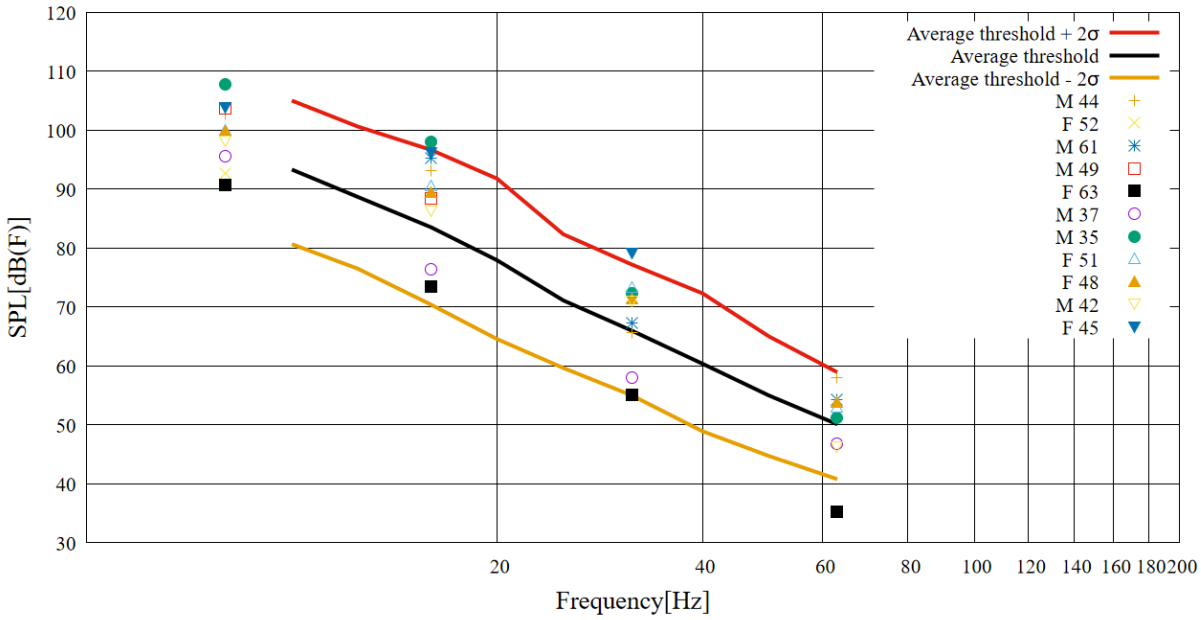

Figure 2 Threshold of complainants with correspondence

As shown in Figure 2, the thresholds of complainants mainly fall within the range of the average threshold of university students plus/minus two times of the standard deviation [7]. The authors and Inukai measured approximately 50 complainants in total, but not a single person had exceptionally low threshold. The possibility that complainants have especially low threshold is nonexistent. Even among university students and the general population, no individuals with exceptionally low-level threshold have been found. It is simply the degree of individual variation.

The author measured the threshold of a person (female) described in a Ministry of the Environment report as having exceptionally low-level threshold. When the level was adjusted manually, the threshold varied greatly. When the sound was increased slowly, the button was pressed at a very low level. When increased quickly, the threshold became high. The psychological afterimage of sound was strong, and the person reacted even when no sound was present. The threshold did not differ greatly from that of ordinary people. The thresholds of complainants are sometimes high because of their age. There is no finding that they differ from the general population. The thresholds of university students are low because they are

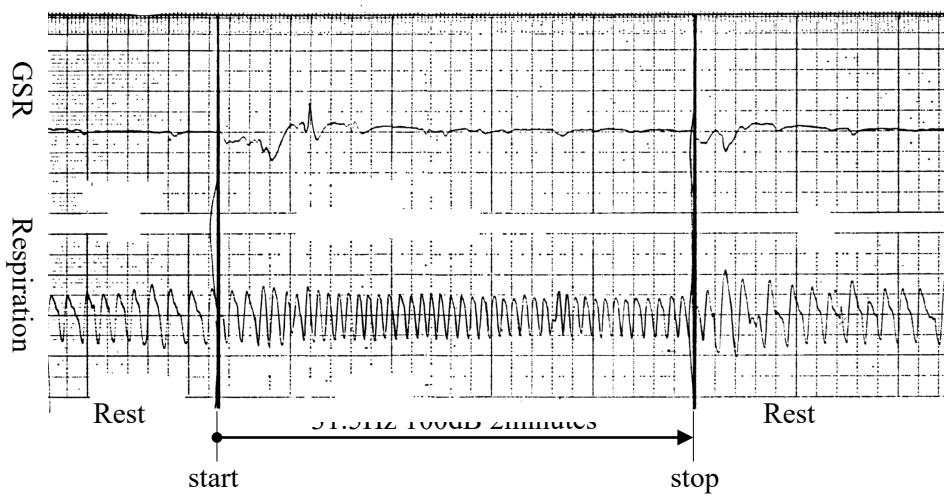

Figure 3 Physiological Response of Galvanic Skin Response and Respiration

young.

GSR shows reactions immediately after the onset and immediately after the end of the sound. The complainant (male) shown in the figure 3 is one with correspondence. The respiration waveform becomes faster while the sound is present, and becomes slower and calmer when the sound ends [1,6].

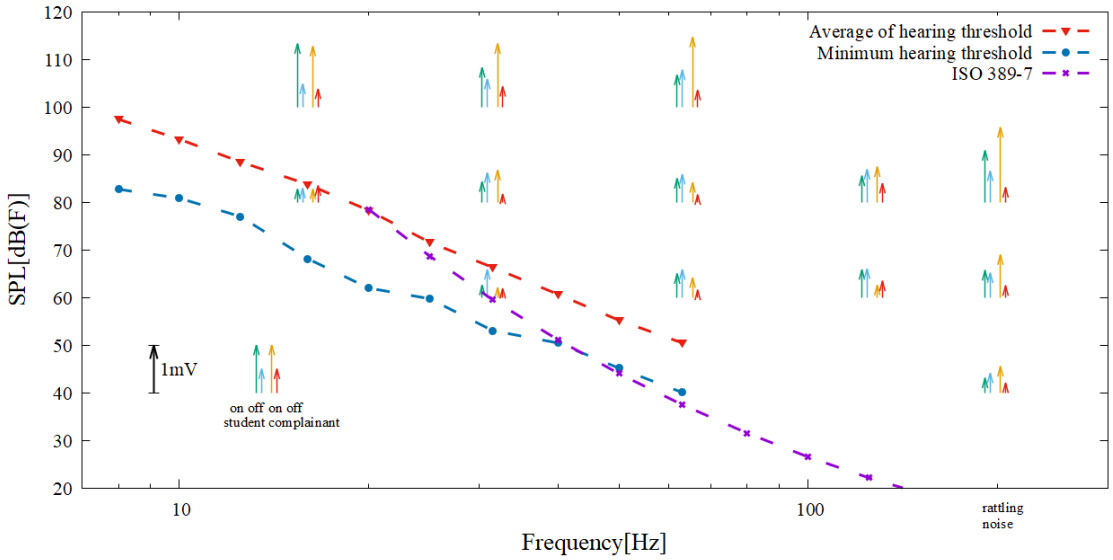

Figure 4 Average of galvanic skin responses of 9 university students and 11 low frequency noise complainants with correspondence

From Figure 4, GSR (galvanic skin response), which is closely related to the threshold, does not differ much between complainants and students. In both groups, the reaction becomes very small as the level approaches the hearing threshold [1].

University students do not have much responses on respirations rate. The general population also have not much responses on respirations (not shown in the figure).

Complainants with correspondence show physiological reactions. Since reactions also occur with frequencies different from those at the complaint site, or with ordinary noise such as rattling sounds, it is considered a stress reaction in a broad sense. For complainants without correspondence, it is unknown whether physiological reactions occur or not, because experiments have not been conducted.

SEVERAL PROPOSALS FOR SOLVING NOISE AND LOW-FREQUENCY NOISE PROBLEMS

(1) Complaints exist, and therefore research on noise is necessary. Complaints are an important research theme.

(2) Although noise and low frequency noise exist, if human relationships are good, unpleasant feelings are reduced and complaints are not so many. When building a house, the locations of outdoor units, water heaters, and similar equipment should be communicated to neighbors. Equipment should be placed on the south side as much as possible. While considering the mechanism of sound generation, both the sound-source side and the receiving side have to seek the good position to put the equipment. This is the same idea as in the Evaluation Guide" to Solve Low Frequency Noise Problems [3,4]. Engineers who manufacture air conditioner outdoor units and water heaters are making efforts to reduce noise. However, when the

distance between each house is extremely small, it is impossible to completely eliminate audible sound. It is desirable for each home appliance manufacturer to sell soundproof covers.

(4) The term “infrasonic noise” should be discontinued. It tends to be used to support the opinion that although it cannot be heard, it has harmful effects on the human body. It is simply that the threshold is high; if the level is high enough, it is perceived. Even at 1000 Hz, if the level is low, it cannot be heard. Academic terminology should be determined based on facts.

(5) If a headphone-type experimental device on low-frequency noise can be developed, it will be effective on-site. By having complainants experience low-frequency noise through headphones, they can understand with the real sense what low-frequency noise is like. This may be effective for complainants without correspondence. If complainants can experience low-frequency noise through headphones and have their individual thresholds can be measured, it becomes much clearer whether the measured data on cite can be perceived or not. The possibility of progressing toward resolution increases.

(6) Active approaches for complainants without correspondence are being sought, but have not been found. Is it possible for family members to understand low-frequency noise and establish a cooperative system with the complainant?

(7) The Non-Profitable Organization “Association for Considering Noise, Vibration, and Low-Frequency Noise in Residential Environments” conducts consultation activities for complainants. But the consultation is not sufficient now for whole Japanese complainants.

9. ROLE OF LOCAL GOVERNMENTS

(1) In departments of local governments some section of environment accepts complaints regarding noise and low-frequency noise. However, among these, there are special cases in which psychological problems and other issues are involved, and coordination with other departments or communication with public health centers may be necessary. Any complaint should first be accepted, and depending on the content, it should be forwarded to the relevant department. Each local government is the final guardian of a good living environment and serves as a place of refuge. They should function as a “quick response section.”

(2) For resolution, discussions between the sound source side and the receiving side are necessary. Local governments should mediate between the two. Even for complainants without correspondence, if problems are occurring in daily life, local governments should provide some consultation. Municipal officials should be people who possess kindness toward others and should ideally be versatile individuals.

(3) Land use regulations in Japan are too lenient.

(4) Measurements by Municipal Officials

New measuring instruments can continuously record sound for three days and can also store some analysis results. The task of the official is only to set the measuring instrument on-site and retrieve it three days later. However, for municipal officials to confirm the correspondence between the complainant’s complaint and the operating condition of the sound source, a very large amount of effort and labor is currently required.

By developing programs using artificial intelligence, operation time, frequency characteristics, complaint times, etc. are calculated by the three days record automatically. Local officer can use much time for counseling of complainants. Many local officers are graduated from humanities fields, and they can support the complainant that includes the human element, which only humans can do.

CONCLUSION

From the experience of dealing with complaints scientifically regarding noise and low-frequency noise, acoustic countermeasures, clarification of the mechanisms of unpleasant feeling and adjustment of human relationships for problem solving are measures for resolution. Complainants and all people involved are human beings. If we respect each other with the spirit of freedom, equality, and fraternity, which are the essence of democracy, we can mutually understand one another and create a good path toward resolution.

Acknowledgements

This report has been created through interactions with many people, including complainants of noise or low-frequency noise, researchers, students, and others. We would like to express gratitude to many people.

Consideration has been given to the safety and privacy of complainants in conducting research and consultation activities.

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The design, implementation, and testing of a measurement microphone based wind turbine noise measurement and analysis system

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ABSTRACT

This paper presents work on the design, implementation, and testing of a measurement microphone-based wind turbine noise (WTN) measurement and analysis system. This includes the design of a dual dome windshield for WTN measurement as specified in standard IEC 61400-11, and testing of this in an anechoic chamber to compare with other commercially available windshields, including frequency response and wind noise attenuation. The dual-dome windshield was then used with a measurement microphone (Earthworks M30) to conduct WTN measurements in-situ. The obtained audio recordings were calibrated to A-weighted sound pressure levels (SPLs) in third octave bands, logged at 100 ms to enable the analysis of WTN amplitude modulation (AM) using the IEC 61400-11 recommended method. The calibration implementation was verified with reference to a Class 1 sound level meter; the code used is available as an open-source resource. The calibrated results were then used to evaluate the AM characteristics of the recorded WTN. The finished product is shown to be suitable for the measurement of WTN and the analysis of low frequency information, including the identification of other amplitude modulation (OAM) noise characteristics. Future work will conduct a listening test focusing on the effect of normal amplitude modulation (NAM) and OAM on noise perception, taking sound pressure levels, modulation depth and intermittence into account.

INTRODUCTION

This paper presents the design and testing of a dual-dome windshield for wind turbine noise (WTN) measurement following standard IEC 61400-11 [1]. Whilst previous research has made use of such equipment [2-4], the details of the design and testing processes have not been made widely available. WTN is characterised by normal amplitude modulation (NAM) and other amplitude modulation (OAM); OAM has a higher magnitude in a lower frequency range and a higher modulation depth than NAM, but is intermittent, whereas NAM is periodic [5-7]. Ioannidou et al. examined the perception of NAM and OAM using synthesised stimuli; the listening test results show that due to its intermittence, even with a higher modulation depth, OAM does not lead to greater annoyance compared to periodic NAM with a lower modulation

depth [7]. This paper is part of wider research that aims to further investigate the perceptual annoyance of NAM and OAM using in-situ WTN recordings, following Ioannidou et al.'s study [7]. IEC 61400-11 recommends sample code for analysing and rating amplitude modulation (AM), developed by the UK Institute of Acoustics (IOA) Amplitude Modulation Working Group (AMWG) [8]. A calibration implementation was undertaken to enable this analysis method, thereby allowing for the identification of OAM of in-situ recordings; resulting code is available as an online resource [9].

The structure of the paper is as follows: the background section introduces the standard procedures for measuring and analysing wind farm noise, including the recommended windshield system. The following section then presents the design and the testing of the effectiveness of the windshield, including comparison with other commercially available windshields. This comparison includes results from two experiments, one covering insertion loss measurement, and the other comparing wind noise reduction. The use of the finished system to conduct in-situ recordings is then reported, followed by details on the calibration of the recorded audio signals to measured sound pressure levels (SPLs), and the identification of OAM characteristics of wind turbine noise. The paper concludes with a statement of the key findings of this work and a discussion of future work.

BACKGROUND

IEC 61400-11 specifies standardised procedures for the measurement and analysis of wind turbine noise [1]. A Class 1 sound level meter (SLM) is recommended for data collection, which should have a flat frequency response from 10 Hz to 10 kHz. Measurements should include A-weighted SPLs, A-weighted or Z-weighted 1/3-octave band spectra, and narrow band spectra, depending on the purpose of the study.

The highest A-weighted SPLs are typically expected in the downwind direction relative to the wind turbine, though this may vary depending on the specific noise characteristics of interest [1]. For instance, the most prominent tonal noise may not occur in the downwind direction, partly due to the lower aerodynamic masking sound. NAM is mainly perceived in the crosswind direction; OAM is mainly perceived in the upwind or downwind directions [5,6,10]. It is typically recommended that the measurement distance for noise analysis is the sum of the hub height and a single blade length [1-3]. Other non-acoustic measurements are also recommended besides noise measurements, including meteorological data (e.g., wind speed, humidity, temperature, and rain).

IEC 61400-11 recommends a sample code for analysing and rating amplitude modulation (AM), developed by the UK Institute of Acoustics (IOA) Amplitude Modulation Working Group (AMWG) [8]. The input data for the IOA AMWG method requires A-weighted, band-filtered 100-ms Leq values; the three frequency bands are 50 - 200 Hz, 100 - 400 Hz, and 200 - 800 Hz, which should be summed (logarithmically) within each band from third-octave band results [8]. The outcome of the method allows for the identification of amplitude modulation, the modulation depth in each frequency range, the modulation frequency (i.e., blade pass frequency), prominence, and reconstructed signals. Prominence is the ratio between the modulation frequency and the masking level, indicating the relevance of the calculated modulation depth to turbine operation. The IOA AMWG determines that a prominence level below 4 indicates no AM. Reconstructed signals represent amplitude modulation (AM) signals solely associated with wind turbine operation, with background noise effects minimised. This is achieved by de-trending the input time-series data, applying Fourier analysis to obtain the power spectrum of the fundamental modulation frequency (FMF), and then performing an inverse Fourier transform to reconstruct a 'clean' AM time series related only to the FMF [8].

In order to minimise the effects of wind gusts and wind-induced noise, the use of a primary wind screen and a secondary screen is recommended by IEC 61400-11 [1]. The wind screen should be spherical or ellipsoid in shape and made of porous materials. To eliminate ground reflections the microphone should be placed at ground level on a 1-metre-wide board. Previous research has made use of dual-dome windshields in wind farm measurements [2-4]. Wszołek et al. [4] compared the effectiveness of different windshields and found that dual-dome windshields performed best in the low-frequency range. An insertion loss measurement in still air is also suggested to correct the frequency response of the windshields [1]. Hansen et al. conducted an insertion loss test in an anechoic chamber using low-pass filtered (at 200 Hz) white noise, comparing conditions with and without a windshield [11].

IMPLEMENTATION OF THE WINDSHIELD

This section introduces the design of the dual-dome windshield, following the IEC 61400-11 standard requirements and ensuring ease of transport [1]. The effectiveness of the dual-dome windshield was evaluated by comparing it with other commercially available windshields, investigating the frequency response and wind reduction performance. The same approach was used to test the performance of the dual-dome windshield itself by comparing with and without the windshield conditions on the base-board.

Design and construction of the windshield

The windshield consists of a circular acoustic reflector 1000 mm in diameter, with built-in dual concentric fabric hemispheres of 130 mm and 600 mm diameters. The microphone is positioned with its capsule at the centre point. The windshield setup is shown in Fig. 7. The exploded diagram of the dual dome windshield design is shown in Fig. 1. To aid portability, the windshield is constructed of several sections. The base board is made from CNC-machined 19mm MDF in two halves, assembled into position using aluminium profile sections underneath, and includes appropriate recesses to flush-mount the two domes. It also includes a recess and 3D-printed insert to securely mount the microphone such that its capsule is flush to the surface at the exact centre of the board. The domes are each constructed of a rigid ring that sits in the appropriate recess on the board, with eight equally-spaced ribs that meet at the apex. These are 3D-printed from polyethylene terephthalate (PET), which allows the structure to be strong and lightweight. The ribs have hexagonal sections, with circumdiameters of 3mm and 6mm. The fabric coverings of the domes are made from open-weave polyester commonly used in speaker and acoustic panel coverings. Each is sewn together from eight laser-cut sections and pulled taut over its frame.

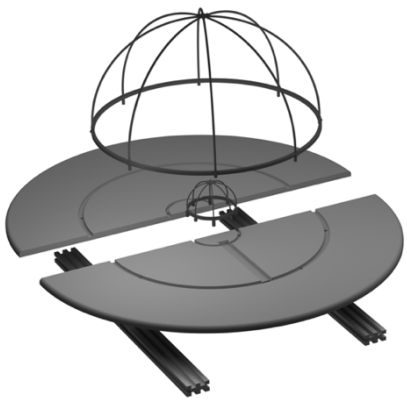


Figure 1: An exploded diagram of the dual-dome windshield design. The base board has a diameter of 1000 mm, the built-in dual concentric fabric hemispheres of 130 mm and 600 mm diameters.

Comparing with commercially available windshields

The windshields used in this test include a fitted foam shield, an M30 measurement microphone factory windshield for outdoor recording, and a Røde Blimp - an enclosed shotgun-style shield with a close-fitting DeadWombat windjammer. Røde windshields are an industry standard solution, with this and equivalent models citing a wind noise attenuation of up to 30 dB, and acoustical transparency characteristics [12,13].

The insertion loss of each windshield was determined by conducting an impulse response (IR) measurement using the exponential sine sweep (ESS) method [14]. A Genelec 8130A loudspeaker was used to reproduce a sine sweep of 10 seconds duration with a frequency range of 40 Hz - 20 kHz (fs = 48 kHz). An M30 measurement microphone was used, positioned at a height corresponding to the centre of the loudspeaker, and kept fixed throughout the recording. The impulse responses were recorded with the bare microphone and under different windshield conditions. The dual-dome windshield was set up in free-field for direct comparisons, as shown in Fig. 2(a).

(a) Insertion loss experiment (b) Wind noise attenuation experiment

Figure 2: The setup for comparing with commercially available windshields experiment in the anechoic chamber. In (a), the dual-dome windshield was set up in free-field, the windshields were positioned with the elevation similar to angle between the turbine hub and the measurement point. For the wind noise attenuation, the dual-dome windshield was set up in the same way.

The insertion loss of each windshield was assessed by subtracting the with-windshield condition from the microphone-only condition in the frequency domain; the comparisons of all windshields were analysed spectrally, as shown in Fig. 3. The M30 fitted foam shows minimal magnitude differences across the frequency range, demonstrating the least effect on the frequency response. The Blimp windshield itself shows an insertion loss dip (-4.6 dB) at around 4 kHz, and then a drop-off again above 7 kHz; the Blimp windshield with the windjammer shows an insertion loss of over 5 dB above 3.8 kHz, with the greatest magnitude difference (-17.8 dB) found at 8.4 kHz. Similar to the Blimp windshield, the small dome indicates a dip at 4.7 kHz with a difference of -4.7 dB, although the magnitude differences are within 2 dB above 5 kHz. The big dome indicates better performance than the small dome; the maximum insertion loss (-2.4 dB) is found at 4 kHz, and differences above 5 kHz are minimal. The dual-dome condition shows an insertion loss of about -4 dB between 3 kHz and 5 kHz; the performance above 5 kHz is similar to that of the small dome. In general, the dual-dome windshield demonstrates that the insertion loss below 2.7 kHz is minimal; a relatively small effect is shown at high frequencies (above 5 kHz), which is better than the performance of the Blimp windshield.

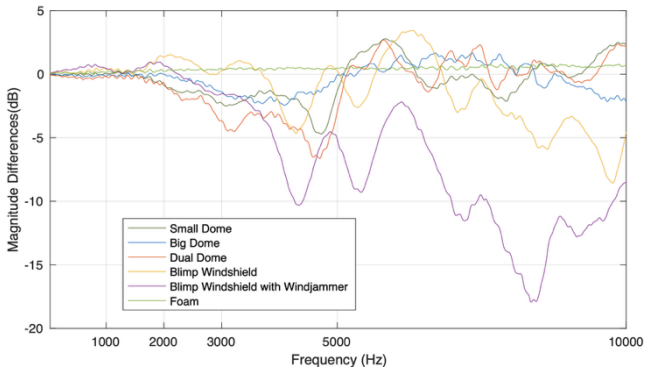


Figure 3: A spectral comparison plot of different windshield insertion loss. Spectral smoothing was applied on each windshield result before the comparison analysis.

The wind noise attenuation experiment setup included a fan generating an approximate laminar flow at a wind speed of around 4 m/s in free air, and two M30 measurement microphones used to measure the wind noise (as shown in Fig. 2(b)). The on-axis microphone was set up on the Blimp boom, situated inside the wind flow; the off-axis microphone was set up with relatively minimal wind flow. Each windshield was set up on the on-axis microphone, and recordings were made simultaneously from both microphones. The wind noise reduction of each windshield was assessed by subtracting the on-axis results from the off-axis results.

The comparisons of the wind noise reduction for each windshield were analysed in the frequency domain; the magnitude differences between the on-axis and off-axis results are shown in Fig. 4. The peak at around 830 Hz, visible across different conditions, is due to the interaction of the wind with the microphone capsule. The on-axis microphone without a windshield is used as a reference to demonstrate the effect of the wind flow. Above 1.5 kHz, the wind noise reduction is similar for all windshields, except for the Blimp windshield with the windjammer, which exhibits negative noise reduction above 5 kHz due to the synthetic fur material of the windjammer. Up to 1.5 kHz, the foam windshield shows the least wind noise reduction, followed by the small dome and the Blimp windshield. It should be noted that the small dome was positioned in free-field as the turbulence created at the ring of the dome would have had an impact on the microphone. The big dome, the Blimp windshield with the windjammer, and the dual-dome windshield show the best wind noise reduction results. In summary, the dual-dome windshield demonstrates the best wind noise attenuation performance.

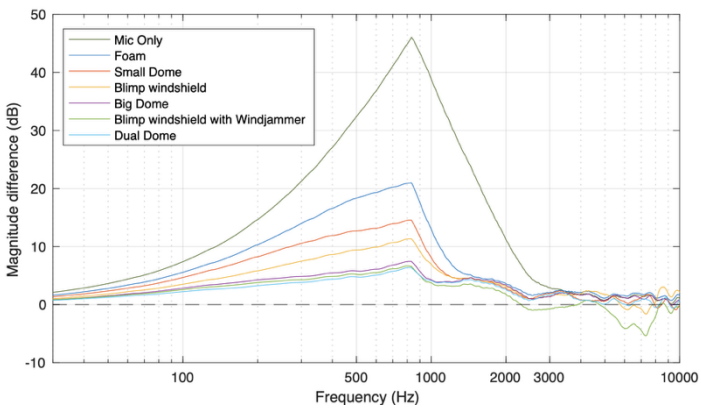
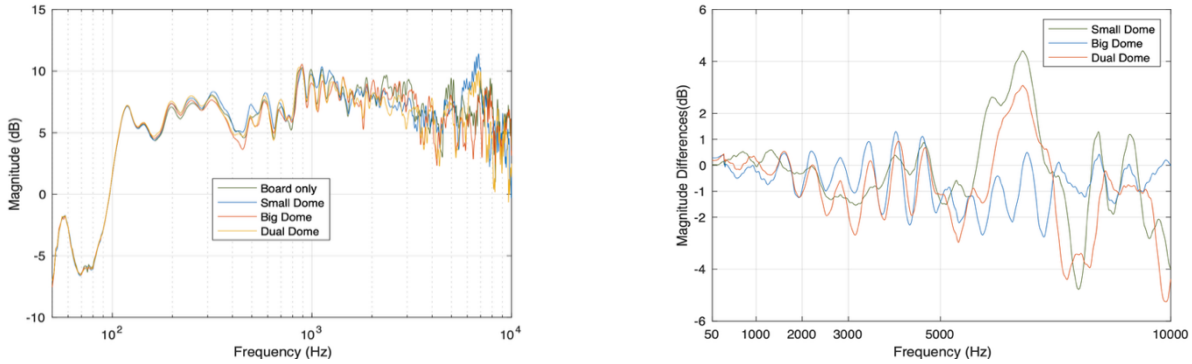


Figure 4: A spectral comparison plot of different windshields on wind noise reduction. Spectral smoothing was applied on each windshield result before the comparison analysis.

Testing the performance of the windshield

To evaluate the performance of the dual-dome windshield, the insertion loss test and wind reduction test were carried out comparing with and without the dual-dome windshield on the base-board. The same methodology from the previous insertion loss test was used, although the setup considered the elevation angle between the turbine hub and the measurement point, typically around 35°. The loudspeaker in this case was placed horizontally to ensure that frequencies were emitted at the same height. Fig. 5(a) shows the frequency spectrum of the microphone on the board with and without windshields; Fig. 5(b) shows the smoothed spectrum magnitude differences compared with the no-shield (i.e., microphone on the board) condition.



(a) Frequency spectrum plot of all conditions (b) Spectrum magnitude difference plot

Figure 5: Results of the dual dome windshield insertion loss test. (b) shows the spectral differences between each case and the base board.

Fig. 5 shows that the frequency response of both windshields aligns generally well with the no-shield condition up to 2 kHz; the differences are within ±1 dB, which is sufficient for the purpose of analysing amplitude modulation using the IOA AMWG method [8]. The spectrum magnitude difference plot in Fig. 5(b) indicates that the small dome has a larger effect on the frequency response above 5 kHz, while the big dome has a larger effect below 5 kHz. The big dome, once mounted on the board, exhibits periodic interference consistent with its physical dimensions, with an amplitude of approximately ±1.5 dB. This is broadly consistent with the impact of the Blimp windshield in the previous measurement and does not pose a significant problem for the intended use of the windshield.

The wind noise attenuation test setup was the same as in the previous test, comparing the windshield performance with the no-shield condition. Fig. 6 shows the wind noise reduction in the frequency domain, illustrating the magnitude difference when comparing the on-axis results to the off-axis results.

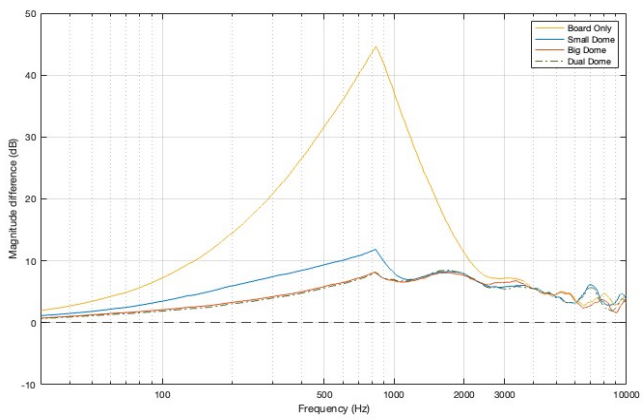


Figure 6: A spectral comparison plot of dual domes on wind noise reduction. Spectral smoothing was applied on each windshield result before the comparison analysis.

The attenuation above 1 kHz shows a consistent magnitude difference of about 5 dB. This is likely due to the effect of the board itself on the airflow. The wind noise reduction results are similar to those of the dual domes in free-field, while the small dome shows better wind reduction because of the presence of the board. In general, the big dome has better wind noise attenuation characteristics than the small dome, with the combination of both domes providing even better performance for high-wind situations.

RECORDING WTN IN-SITU

A wind farm recording was conducted at Hook Moor Wind Farm, Parlington, Leeds, UK. The site consists of 5 wind turbines (tip height 125 m) with an electricity generation capacity of up to 10 MW [15]. Given that the purpose of the recordings was WTN amplitude modulation analysis, the microphone used was an Earthworks M30 measurement microphone, which has a flat frequency response from 3 Hz to 30 kHz [16]. A Zoom F8 audio recorder was used for this acoustic measurement. The recording position was downwind of the nearest turbine at a distance of 50 m; this location was constrained by limited access along the public footpath. Fig. 7 shows a picture of the recording setup with the dual-dome windshields.

(d)

(d)

Figure 7: Dual dome windshields setup at downwind of the nearest turbine at a distance of 50 m.

The recordings captured a clear turbine blade swish from the closest turbine, with limited ground reflection and wind-induced noise; the audio then allows for the analysis of amplitude modulation, which is introduced in the next section.

CALIBRATING RECORDED AUDIO SIGNALS TO SPLS

The purpose of calibrating recorded audio signals to SPLs is to conduct AM analysis by utilising the IOAAMWG method [8]. This section introduces the development and evaluation of the calibration system, and the identification of OAM through this methodology.

Calibration methodology

In order to calibrate recordings of WTN using this method, a recording of a 1 kHz tone calibrated to a known level needs to be used as a reference. The calibration process is shown in Fig. 8. The calibration implementation adopted the MATLAB octave toolbox [17] and

modified by increasing the filter order for the third-octave band analysis (increasing from 3 to 7); the resulting code is available in [9]. This work was based on the following standards: IEC/CD 1672: Electroacoustics-Sound Level Meters, IEC, Geneva, Nov. 1996, for A- and C-weighting filters [18]; ANSI S1.1-1986 (ASA 65-1986): Specifications for Octave-Band and Fractional-Octave-Band Analog and Digital Filters, ASA, New York, 1993, for octave and one-third-octave filters [19].

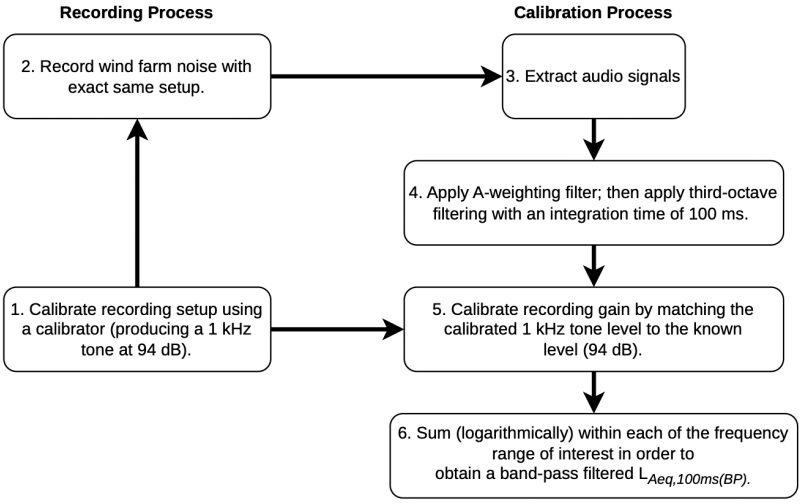
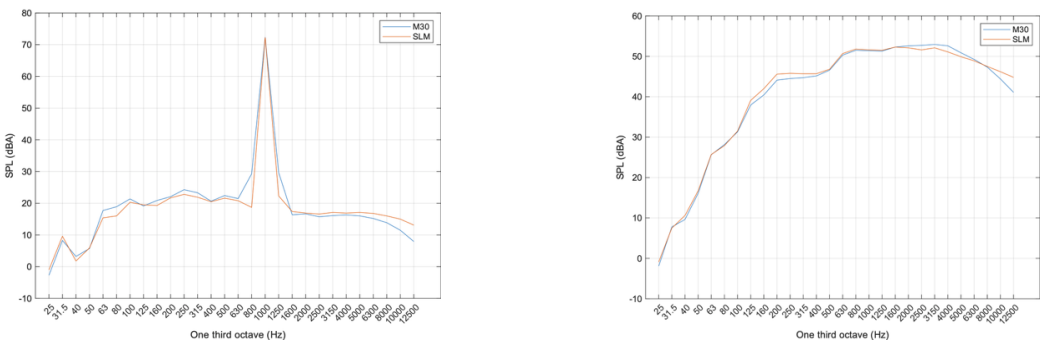


Figure 8: A flowchart diagram of calibrating wind turbine noise signals to A-weighted, band-filtered 100 ms L_{eq} values.

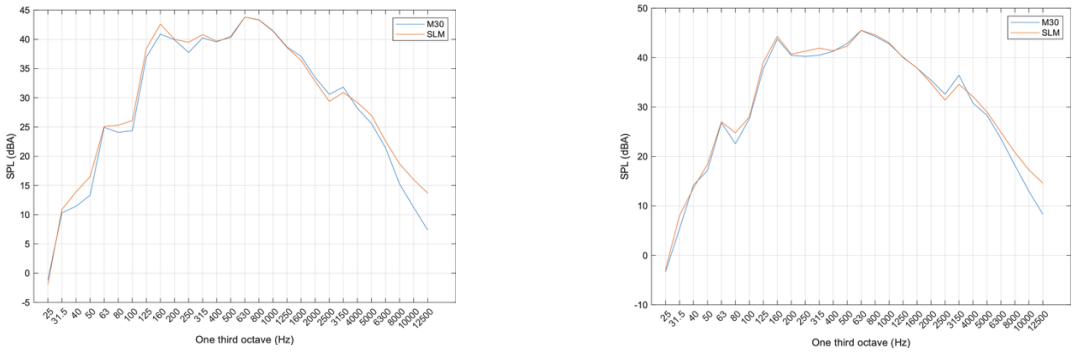
Evaluation of the calibration implementation

To evaluate the calibration implementation, experiments were conducted to compare the calibration results using an M30 measurement microphone with the results from a Class 1 SLM, which meets the IEC 61400-11 standard requirements [1]. The SLM used was an NTI XL2 sound level meter paired with an M4260 measurement microphone. The results compared A-weighted SPLs in third-octave bands logged at 1 s intervals.

The initial evaluation was conducted using a 1 kHz tone, pink noise, and a wind turbine noise recording played back over a single loudspeaker. The M30 microphone and the SLM were set up about 1 m from the speaker and placed as close together as possible. Fig. 9 shows the comparison results for the steady sound sources (i.e., the tone and pink noise) and randomly selected samples of a WTN recording. The steady sound source results show great similarities across the frequency range from 25 Hz to 12.5 kHz; the calibrated 1 kHz tone result shows a less sharp drop-off at adjacent bands. Similarly, for the WTN recording results, the calibration implementation shows reliable results for non-steady noise sources. There is a slight drop-off above 6300 Hz in the calibration results; given that the frequency range of interest for the study is below 800 Hz, the implementation is sufficient.



(a) 1 kHz tone (b) Pink noise

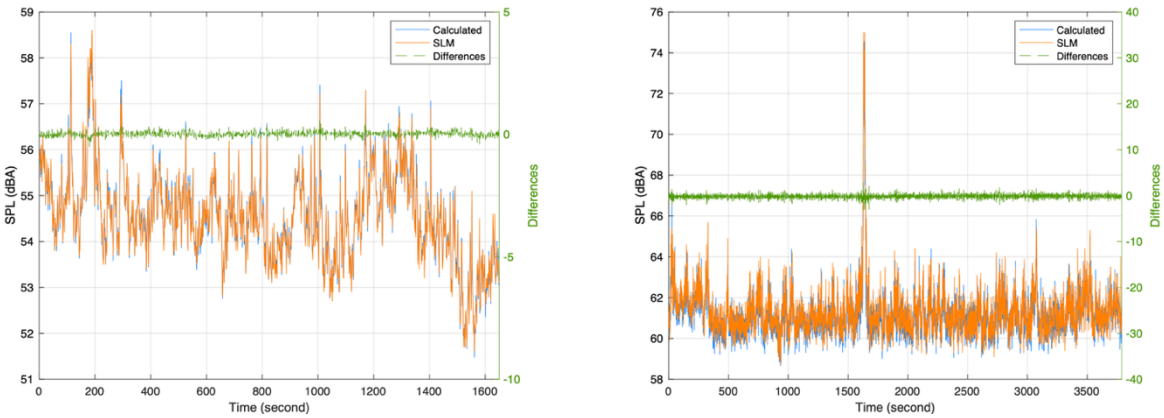


(c) WTN recording (d) WTN recording

Figure 9: Comparison plots of calibration implementation results and a Class 1 SLM results. The results are in A-weighted SPLs in third octave bands logged at 1-second.

The same comparison was carried out in-situ at the Hook Moor Wind Farm. It should be noted that, as the windshields were still in development at this stage, this experiment was conducted using the prototype oversize windscreen with a fitted foam on microphone windshield as the total setup. The experiments were conducted on two separate days under different wind conditions. The wind speed measurement was taken near the recording setup using a hot-wire anemometer. The results were obtained by taking the average over a minute prior to the recording. Hence, the wind speed results did not comply with IEC 61400-11 standards, but were used as a reference in this study.

The results compared A-weighted SPLs logged every second over the entire recording period. Fig. 10 shows the results: the left y-axis shows the SPLs (dBA) of both devices, and the right y-axis shows the level difference between the two. The maximum differences under a wind speed of 3.55 m/s are ±0.6 dBA, with a cross-correlation R-value of 0.993, and very strong statistical significance ($p < 0.001$). For the 7.25 m/s wind speed condition, the maximum differences are ±2 dBA with a cross-correlation R-value of 0.91, and very strong statistical significance ($p < 0.001$). The level variation is more distinct under windier conditions. Given that there might be minor errors in the synchronisation and that the correlations were very strong, the calibration implementation for the A-weighted SPLs case is sufficient.



(a) Wind speed approx. 3.55 m/s (b) Wind speed approx. 7.25 m/s

Figure 10: Comparisons of $L_{Aeq,1s}$ of calibration results and SLM. The left y-axis shows the SPL (dBA) results over time of both calibration and SLM results; the right y-axis shows the level difference between the two over time. In (b), the peak SPL at around 1600 second was due to the plane flying pass.

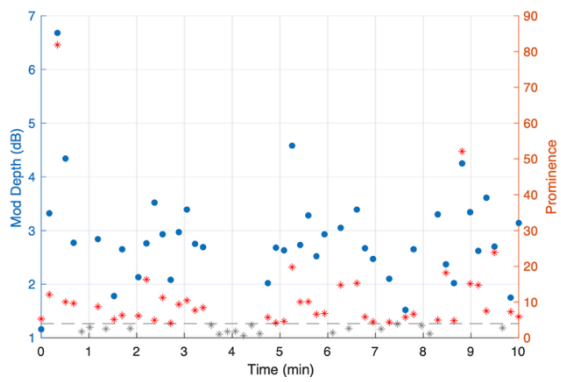
An analysis was also conducted comparing the A-weighted SPLs in third-octave bands logged at 1 s intervals; the level differences for each octave band per second were averaged over the entire recorded period, which is shown in Table 1. The results show a similar trend in drop-off above 6.3 kHz. Below 800 Hz, the variation is within ±1 dBA, which is insignificant.

Table 1: The average difference of A-weighted SPLs in third octave band logged at 1-second. Results were calculated by subtracting the calibration results from the SLM results.

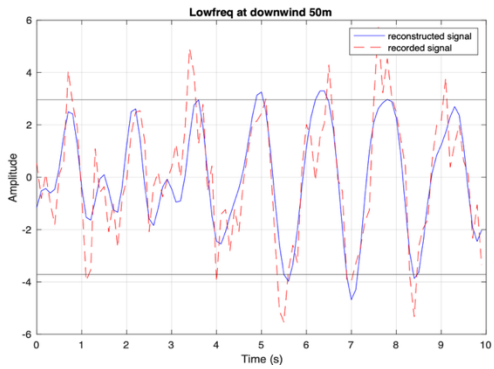
Frequency (Hz)	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**
Differences (dBA)	0.40	-0.01	-0.25	-0.39	-0.58	-0.58	-0.71
Frequency (Hz)	**125**	**160**	**200**	**250**	**315**	**400**	**500**
Differences (dBA)	-0.82	-0.80	-0.98	-1.05	-0.89	-0.47	-0.10
Frequency (Hz)	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**
Differences (dBA)	0.19	0.05	0.13	0.18	0.32	-0.08	1.62
Frequency (Hz)	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**	**12500**
Differences (dBA)	0.90	0.75	0.21	0.03	-1.16	-2.88	-5.68

Amplitude modulation analysis of the WTN recordings

The calibration implementation has given sufficiently accurate results for the frequency range of interest; the analysis of amplitude modulation using the IOA AMWG method [8] was then conducted. This section presents the results from the previously mentioned WTN recording under the 7.25 m/s wind speed condition; the recording position was 50 m downwind of the turbine. The modulation frequency was stable at 0.7 Hz for 66% of the recording duration. Fig. 11(a) shows the modulation depth and its corresponding prominence in the low-frequency range (50 - 200 Hz) over a 10-min duration. Previous literature has suggested that an amplitude modulation with a modulation depth above 6 dB below 400 Hz can be identified as OAM [5,6,20]. At the start of the recording, a modulation depth of 6.68 dB in the low-frequency range was found, with a prominence value of 82 indicating the occurrence of OAM. A modulation depth of 5.54 dB was also found in the mid-frequency range (100 - 400 Hz) within the same 10-second block, with a prominence value of 103. Fig. 11(b) shows the reconstructed amplitude modulation signals plotted against the recorded signals for the low-frequency range. It can be clearly identified that OAM occurs between 4 and 10 seconds; the modulation depth increases from 5 dB to 6.68 dB, the auditioning found that there is a clear transition from “swish” sound to “thump” sound.



(a) Modulation depth plotted against its corresponding prominence.



(b) Reconstructed amplitude modulation signals plotted against recorded signals.

Figure 11: Amplitude modulation analysis using IOA AMWG method [8]. In (a), detected modulation depth is shown as blue scatter points (left y-axis) and its corresponding prominence is shown as red scatter

points (right y-axis) at the low frequency range over time. Each scatter point represents the modulation depth of a 10 second duration.

CONCLUSION

This paper has presented a wind turbine noise measurement system, detailing the design and insertion loss testing of the dual-dome windshield. As part of the measurement system, a measurement microphone-based system was also implemented for capturing sound level data with reference to a Class 1 sound level meter. This system allows for in-situ measurements and the analysis of the amplitude modulation characteristics of wind turbine noise, following the IEC 61400-11 standard [1].

Comparisons with commercially available windshields have shown that the foam windshield has the least effect on the frequency response, while its wind noise reduction is not significant. The Blimp windshield and windjammer demonstrate a minimal effect on insertion loss up to 3 kHz, although the insertion loss exhibits a significant negative effect above 4 kHz. The Blimp windshield's wind noise attenuation of up to 30 dB has also been verified, with the windjammer further reducing the wind noise level. A negative noise reduction has been found due to the effect of the windjammer, which may be attributed to its material. The insertion loss of the dual-dome windshield is slightly inferior to that of the Blimp windshield with the windjammer between 2 kHz and 3.5 kHz; however, at frequencies above 5 kHz, it demonstrates reduced insertion loss relative to the Blimp windshield itself. In the wind reduction experiment, the dual-dome windshield showed wind noise attenuation of up to 35 dB; the comparison results showed similar or even superior wind reduction performance compared to the Blimp windshield with the windjammer. The insertion loss test of the dual-dome windshield itself was found to be within ±1 dB below 2 kHz; given that the frequency range of interest for AM analysis is between 50 Hz and 800 Hz, the dual-dome windshield is sufficient for the measurement system.

The calibration system adopted the octave toolbox in MATLAB [17] and modified the results by increasing the filter order, which allows for the calibration of the recorded audio signals to A-weighted SPLs in third-octave bands logged at 100 ms intervals. The implementation was evaluated by comparison with a Class 1 SLM, specifically an NTi XL2 paired with an M4260 measurement microphone. The calibrated steady-source 1 kHz tone results show comparable attenuation in the adjacent bands, reflecting the implementation of a higher-order filter. The $L_{Aeq,1s}$ results of the in-situ WTN were compared; the maximum differences over time were ±2 dBA on a windy day and ±0.6 dBA on a less windy day, and the correlation of both results exhibits very strong statistical significance ($p < 0.001$) . The third-octave band $L_{Aeq,1s}$ results show that below 800 Hz, the variation is well within ±1 dBA. For the purposes of this study, this implementation is sufficient.

Future work will involve conducting a listening test based on this study using in-situ WTN recordings, reproducing the stimuli at the calibrated SPLs. The aim of this listening test will be to investigate the annoyance caused by NAM and OAM.

ACKNOWLEDGEMENTS

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The history of Noise and Health journal - Per aspera ad astra

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ABSTRACT

Noise and Health (N&H) is the only international journal devoted exclusively to research on all aspects of noise and its effects on human health. N&H covers both auditory and non-auditory effects of occupational, environmental, and leisure noise. The journal was founded by Deepak Prasher in 1998 as part of various European Commission–funded projects that he headed from 1994 to 2004. We relied on secondary internet sources addressing the development of N&H (SCImago; Lippincott; DOAJ; Web of Science Journal Info). The journal's impact factor peaked at 1.84 in 2017 and averaged 1.35 from 2014 to 2024. Some notable articles published in the journal have been cited over 200 times. The N&H h-index indicates that 63 articles published in the journal have each received at least 63 citations. The number of published papers per year has risen in the last two years from an average of about 25 to over 100. The overwhelming majority of papers have originated from seven countries: China, India, Germany, the United Kingdom, South Korea, the USA, and Brazil. The percentage of music-related papers in N&H has risen in the last two years from about 5% on average to approximately 25% per year. In conclusion, N&H has experienced both ups and downs throughout its history. Currently, the quality of published papers is improving, and a continued rise in the impact factor is expected. We believe that music, and particularly music therapy in clinical and home settings, deserves greater attention from researchers in the fields of sound and noise.

INTRODUCTION

What makes one international medical journal a good journal? One could immediately think on impact factor, publisher, design, or printing quality. Well, we think it is people. Those who make the journal and the people who write for it.

Noise and Health was founded by Deepak Prasher in 1998 [1]. It was at the ICBEN Congress 1998 in Sydney that Deepak Prasher presented the first issue of Noise and Health, a new specialized journal on health effects of noise. Goran Belojević was a Serbian researcher attending the congress. The two did not know each other or even have a chance to talk. But as time went by, Deepak continued editing Noise and Health, and Goran started writing for it. One of Goran's papers became among the top cited and downloaded in Noise and Health [2]. This likely ignited their acquaintance. They met at Robinson College, Cambridge, where

Deepak organized NOPHER 2001 - An International Symposium on Noise and Health. Deepak followed Goran's subsequent papers in Noise and Health [3-9]. Another opportunity for meeting and conversation was in Kolkata in 2016, at the Third National Conference of Indian Academy of Otorhinolaryngology, Head and Neck Surgery and National Initiative for Safe Sound. There they discussed the journal's future, as Deepak was approaching retirement. In 2019, the journal faced serious financial troubles and a backlog of about 50 papers. Deepak contacted Goran and offered him the editor's position without an honorarium. Goran accepted, and what followed was rising success. The foundation of this success has been an international Editorial Board with a majority of ICBEN members.

MATERIALS AND METHODS

Information regarding the development of *Noise and Health* was obtained from secondary online sources, including SCImago, Lippincott, DOAJ, and Web of Science Journal Info. [10,11].

RESULTS

Past and Present of *Noise and Health*

The h-index of *Noise and Health* shows that 63 articles published in the journal have each been cited at least 63 times [10]. The journal achieved its highest impact factor of 1.84 in 2017, while the average impact factor between 2014 and 2024 was 1.35 (Figure 1).

Figure 1: Impact Factors of N&H year by year for the period 2014-2025

Most of the published articles have come from seven countries: China, India, Germany,the United Kingdom, South Korea, the United States, and Brazil. In addition, the annual number of published papers has increased substantially, rising from an average of approximately 25 articles to 127 in 2025 (Figure 2)

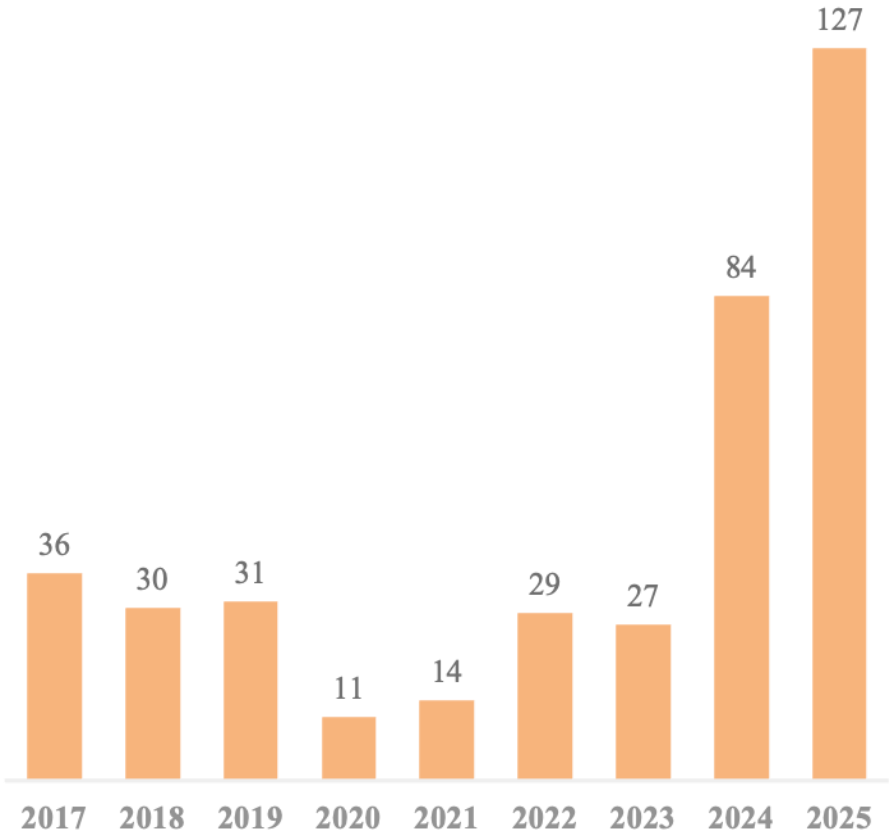

Figure 2: Total number of papers in N&H for the period 2017-2025

During the last two years, the share of music-related publications in N&H has grown markedly, increasing from an average of about 5% to nearly 25% per year (Figure 3).

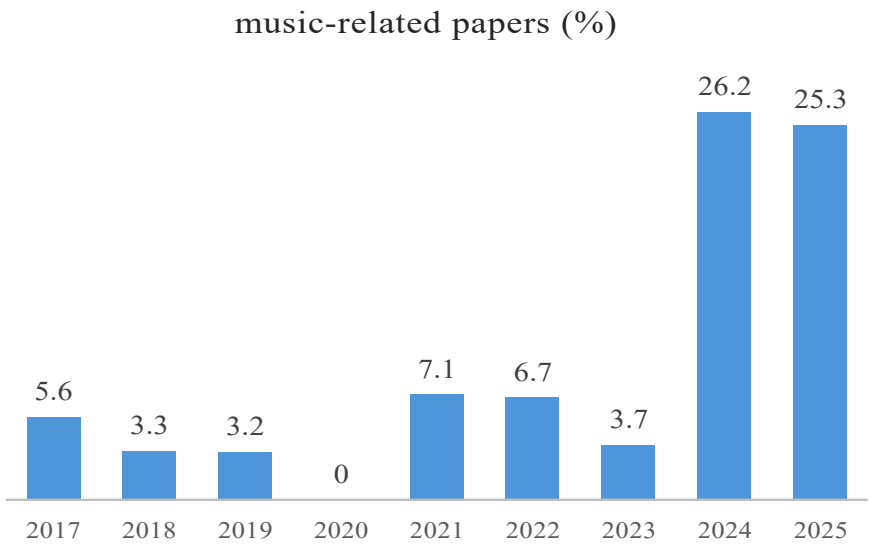

Figure 3: Percentage of papers in N&H dealing with music, from 2017 to 2025

CONCLUSION

In summary, *Noise and Health* has gone through periods of progress and challenges. The standard of published research is advancing, and further growth in the impact factor is anticipated. *Noise and Health* broadly welcomes research on health effects of environmental noise, occupational noise and speech and listening pathology, and other related topics. We point out that music, especially music therapy in clinical and home environments, should also receive focus from scholars studying sound and noise.

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