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Non-Auditory Effects of Environmental Noise

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Editor's Note: The study of non-auditory effects of everyday environmental noise such as sleep disruptions and annoyance are not traditionally part of audiology. Most of the researchers are not audiologists, and the journals, while well-respected and peer-reviewed, are not mainstream audiology publications. This white paper is a primer for this important area of study and will also appear on the Canadian Academy of Audiology website at www.CanadianAudiology.ca.

Preamble

This paper is an overview of the findings in the literature for the subject area of the non-auditory effects due to lower-level environmental noise. Regular reviews have appeared in the literature since the early 1990s (Abel, 1990; Fay, 1991), with the most recent one being van Kamp et al. (2020). Over the past decade, the World Health Organization (WHO) has sponsored several excellent reviews on the effects of stress and cardiovascular effects (Van Kempen, Casas, Pershagen, and Foraster, 2017, 2018; Munzel et al., 2018), sleep disruption patterns (Basner, and McGuire, 2018), cognition (Clark, and Paunovic, 2018), adverse birth outcomes issues (Nieuwenhuijsen, Ristovska, and Dadvand, 2017), and general annoyance (Guski, Schreckenberg, and Schuemer, 2017), and have come out with many general recommendations that communities and jurisdictions should consider in their environmental and building planning processes (WHO, 2018).

This paper will summarize the relevant references and their findings while attempting to delineate many of the inherent difficulties in performing such research. This, in turn, may provide insight into conclusions stemming from the WHO (2018) general recommendations paper.

Indeed, in a recent paper, where only high quality and controlled research was reviewed, it was argued that the WHO (2018) general recommendations paper, may need to be revisited and updated due to the possibility of confounding variables in previously reviewed studies, as well as the inclusion of other environmental noise sources such as wind turbine noise and rail traffic noise (van Kamp, Simon, Notley, Baliatsas, and van Kempen, 2020).

Introduction

While it is well-established that prolonged exposure to sound levels at 85 dBA and higher can cause a measurable permanent sensori-neural hearing loss (ISO-1999, 1990; Roberts and Neitzel, 2019), there are few reliable measures of systemic dysfunction for levels below 80 dBA. (Data show that there may be a slight measurable hearing loss for a sufficiently long exposure of sound levels between 80 dBA and 84 dBA). In addition, reports of non-auditory effects of noise exposure are abundant in the literature with ramifications that can increase stress, disrupt sleep, and be implicated as a factor in language and reading development for elementary-age students in schools.

Some of the literature is contradictory, some reports demonstrate slight issues, yet other reports fail to find any systemic effects. Part of the problem is the lack of reliable measures or measures that have only a loose correlation with a systemic pathology. For example, serum cholesterol measures may show a slight elevation in long-term noise exposure, but this should not be taken as an indicator of eventual cardiac pathology. Another example is that environmental noise that creates the greatest sleep disruption may have the lowest annoyance compared to other noise stimuli (see, for example, Elmenhorst et al., 2019).

Only publications that have gone through a rigorous peer academic review will be included. However, despite the research appearing in a peer-reviewed journal, there can still be serious methodological problems that call the results, or lack thereof, into question. Many historical studies have been summarized in the 1991 book *Noise & Health* (Thomas H. Fay, Ed., 1991) and a review article by Abel (1990). Davies and van Kamp (2012) also performed an enlightening review, and the results were similar to earlier publications. For a historical review, these references should be consulted. Following is a summary of the more recent research, which is delineated under four general headings: “Annoyance,” “Stress and cardiovascular effects of noise,” “Sleep disruptions due to noise,” and “Cognitive/educational issues due to noise.”

An inherent problem with examining the relationship between the effects of low levels (below 85 dBA) of environmental noise and non-auditory sequelae is the line between academic integrity and advocacy may be crossed. While it is true that environmental noise exposure may cause some issues in some people, it cannot necessarily be concluded that this would have long-term detrimental consequences. There are no “smoking gun” reports in the literature that environmental noise levels below 85 dBA will cause permanent issues, and this is true of sleep disruption, increased stress leading to cardiac involvement, or long-term educational/language problems. It may be true that some people are more susceptible to environmental noise, and it may be true that the exposure is “dose-dependent,” whereby higher level and/or more prolonged exposure to environmental noise may result in greater annoyance that may have long-term effects. Still, eventual systemic problems such as cardiac issues may also be related to other factors. Low-level environmental noise is just one of many factors contributing to annoyance and possible long-term health issues.

This review will not concern itself with non-human reactions to environmental noise concerning marine life and other wildlife (see, for example, Guan, Scholik-Schlomer, and Pearson-Meyer, 2018 for a review). However, many acoustical associations such as the Acoustical Society of America and the Canadian Acoustical Association have had long-standing committees to investigate the effect of marine and environmental noise on migration patterns, reproductive patterns, and even vocalization changes in animals.

General Overview:

A: Annoyance:

Annoyance is primarily a subjective attribute of a sound or vibration. Annoyance can be related to the uniqueness of a sound, its physical spectral and temporal characteristics, and even whether a person has control over the sound. (Bronzaft and Madell, 1991). Miller (1974) stated that noise "has its base in the unpleasant nature of some sounds, in the activities that are disturbed or disrupted by noise, in the physiological reactions to noise, and in the response to the meaning or messages carried by the noise."

Traditionally "annoyance" has resisted a formal definition since it appears to result from many intrinsic and extrinsic factors, can be dose-dependent, and highly variable among different groups and ages.

Nevertheless, annoyance can be related to some objective measures. This was the basis of much research in the 1950s, 1960s, and 1970s, where the unit "noys" was suggested as a possible measure of annoyance. Spectrally, annoyance appears to be similar to a dB A-weighted noise, except that higher-frequency sounds above 1000 Hz contribute more to a sense of annoyance than lower frequencies and can be shown to correlate with the D-weighted filter on sound level meters (Kryter, 1970). Despite this pioneering work, annoyance (and its various measures) remains a highly variable phenomenon with sometimes poor correlations, such as where noise that creates the greatest disruption in sleep may have a low level of annoyance (see, for example, Elmenhorst et al., 2019).

Fields (1993) examined several personal and situational variables that could potentially be an issue when predicting noise annoyance in residential settings. "The balance of the evidence from 464 findings drawn from 136 surveys suggests that annoyance is not affected to an important extent by ambient noise levels, the amount of time residents are at home, the type of interviewing method, or any of the nine demographic variables (age, sex, social status, income, education, home ownership, type of dwelling, length of residence, or receipt of benefits from the noise source." (p. 2753). However, he found that annoyance is related to the amount of isolation from sound at home and to five attitudes - fear of danger from the noise source, noise prevention beliefs, general noise sensitivity, beliefs about the importance of the noise source, and annoyance with non-noise impacts of the noise source. This author also noted that a small percentage of people were very annoyed even by low environmental noise levels.

Miedemaa and Voss (1999) examined several previous studies where the number of respondees ranged from 15,000 to 42,000 people. They discussed the demographic variables, including sex, age, education level, occupational status, household size, homeownership, dependency on the noise source, and use of the noise source. They also looked at two attitudinal variables- noise sensitivity and fear of the noise source. It was found that fear and noise sensitivity significantly impact annoyance, but demographic factors are much less critical. Noise annoyance is not significantly related to gender but is related to age. The effects of the other demographic factors on noise annoyance are "minimal."

Van Gerven et al. (2009), in examining the effects of self-reported annoyance from environmental noise across a lifespan, found that of almost 63,000 people between the ages of 15 and 102, there was an age-dependent response. The results revealed an inverted "U" pattern, with the youngest and the oldest respondees reporting the lowest levels of annoyance and those around 45 years of age reporting the most significant annoyance. The authors suggested that a linear relationship over the age span would not be useful in modelling annoyance and could explain the variable results of some earlier studies.

In studying the longitudinal effects of changes in road traffic noise, using questionnaires, measures of annoyance, activity disturbances, and psycho-social well-being were evaluated by Ohrstrom (2004). Adverse effects of long-term exposure to a high volume of road traffic were studied in socio-acoustic surveys in over a two-year period where traffic had been decreased by 90% from 25,000 cars/day to about 2400 cars/day. This resulted in a significant decrease in annoyance and activity disturbances and better general well-being. “To be able to use the outdoor environment and to have the possibility to keep windows open is essential for general well-being and daily behavior, which implies that access both to quiet indoor and outdoor sections of the residency is of importance for achievement of a healthy sound environment.” (p. 719). As a fitting last entry in this section, Ohrstrom went on to say that “future studies should focus more on ‘softer’ health outcomes and well-being … and preferably be performed in connection with traffic abatement measures”.

B: Cardiovascular effects of noise:

This title is not only apropos for this section but also the name of a chapter by Lawrence Raymond in Noise & Health edited by Thomas H. Fay for the New York Academy of Medicine (1991). In summarizing some of the limited generalizations that potentially could be made, he stated (p. 28):

“1. Abnormal blood pressure levels can be induced by high noise levels in some animal species, and in humans under some laboratory conditions. The effects in animals have been long-lasting in some studies.

2. The relevance of these finding to human subjects is unclear….it is not known whether controlling noise to levels which do not usually cause hearing loss … leaves any residual risk of causing hypertension…

3. … the intensity-duration relationship has not been studied.”

Richard Sloan (1991), in summarizing the potential cardiovascular effects due to noise exposure, went on to write that despite many inconsistencies in the literature, the noise exposure suggests that (1) exposure to noise is associated with elevations in blood pressure, primarily diastolic blood pressure, and (2) that in general, this effect appears not to habituate over time”. (p. 23). Sloan related these findings to the potential explanation of noise-induced vasoconstriction and its effects on the central blood system.

Some of the methodological and research issues that plagued earlier research (as far back as 1946) have not been adequately resolved. High levels of subject variability, individual susceptibilities with psychological and possibly genetic differences, and lack of physical objective measures that highly correlate with long-term cardio-vascular sequalae remain problematic. Following is a brief overview of some of the approaches, but perhaps only the molecular analysis study of Munzel et al. (2018) shows any real promise of demonstrating any relationship between low-level environmental noise and potential cardiovascular effects.

Basner et al. (2014) attempted to describe, in a review paper, the physiological bases for the effects of lower levels of noise on the body. They describe a generalized stress model whereby contributions are made by both conscious stress brought about by an emotional response due to perceived discomfort ("indirect pathway") and non-conscious physiological responses between the central auditory pathway and different portions of the central nervous system ("direct pathway"). Long-term chronic exposure can create an allostatic load altering a person's homeostatic conditions in this model. This, in turn, can affect the metabolism and the cardiovascular system. (Allostatic load refers to the cumulative burden of chronic stress and life events. When environmental stress exceeds a person's ability to cope, allostatic load ensues). This "stress response" is well-known in the literature and can be implicated in people who report tinnitus, and generalized fear of loud sounds, such as misophonia (e.g., Davis and El Rafaie, 2000)

Walker et al. (2016) sought to examine 10 male subjects on multiple visits over 41 days in a well-controlled laboratory environment. The subjects were exposed to noise levels (below 85 dBA), and the noise was either centred in the 31.5-125 Hz region or the 500-2000 Hz region. Ambulatory electrocardiography (ECG), blood pressure measures, and saliva-based cortisol measures were assessed before and after exposure. Of all the measures, only heart rate variability was found to show a statistically significant change, but only for the lower frequency (31.5-125 Hz) stimulus. There was no statistical evidence for the blood pressure and saliva cortisol measure differences. Although they postulated an allostatic load issue and a generalized stress response, these mechanisms were only hypothetical, and no direct data was supplied to support this conclusion.

Michaud, Feder, Keith, et al. (2016) assessed stress reactions associated with wind turbine noise exposure using self-reported and objective measures. Over 1200 participants between the ages of 18 and 79 who lived between 0.25 km and 11.22 km from wind turbines had exposure of up to 46 dBA outdoor levels of wind turbine-related noise exposure. Regression modeling only accounted for 21–33% of the variance, and many of their measures did not achieve statistical significance. This included the Perceived Stress Scale measures, hair cortisol concentrations, resting blood pressure levels, and heart rate. Of these measures, only the subjective Perceived Stress Scale scores were positively but weakly related to cortisol concentrations and resting heart rate. Regardless of the measured outdoor noise levels from the wind turbines, diastolic blood pressure appeared to be slightly higher among participants who were highly annoyed by the blinking lights on turbines. "Collectively, the findings do not support an association between exposure to wind turbine noise up to 46 dBA and elevated self-reported, and objectively defined measures of stress." (p. 1467)

To examine potential changes at the molecular level, specifically looking at Reactive Oxygen Species (ROS), Munzel et al. (2018) demonstrated that aircraft noise exposure during nighttime can "induce endothelial dysfunction in healthy subjects and is even more pronounced in coronary artery disease patients. Importantly, impaired endothelial function was ameliorated by acute oral treatment with the antioxidant vitamin C, suggesting that excessive production of ROS contributes to this phenomenon." (p. 873). They also describe an animal model of aircraft noise exposure characterizing the underlying molecular mechanisms leading to noise-dependent adverse oxidative stress-related effects on the vasculature.

Van Kempen, Casas, Pershagen, and Foraster, M. (2018), in looking at a review of available data, concluded that "The results of the current review show that at this moment, not enough studies of good quality are available that investigated the impact of noise on the cardiovascular and metabolic system. The plausibility of an association calls for further efforts with improved research methodology. To improve the quality of the existing evidence, more studies with a cohort or case-control design are needed…. We also recommend that more well-designed studies on health effects concerning exposure to wind turbines and rail traffic noise are set up and carried out." (pp. 12-13)

C: Sleep disruptions due to noise:

Similar to the studies concerning the interaction between environmental noise and cardiovascular/stress relationships, the study of sleep disruptions due to low-level environmental noise can be highly problematic. Low-level environmental exposure can be viewed as more problematic with some groups of people, and indeed, during some hours of the day, the 6 PM to 9 PM time surprisingly being the most bothersome (Bullen and Hede, 1983). And many of the studies that have been reported in the literature do not touch on the effects of more recent wind turbine noise exposure, which may turn out to be problematic in some conditions and with some population groups.

Jurriens and colleagues (1983) performed the "1000 night joint European field study of noise effects" and found that the sleep quality was indeed affected negatively after noisy nights, but the results were highly variable. They did see slight decreases in REM (Rapid Eye Movement) sleep during noisy nights, but only by about 6.5 minutes. There were, however, no clear implications for long-term systemic consequences.

Historically, the study of sleep disruptions was based on subjective reports and changes in REM vs. non-REM sleep fractions and alterations in the subjects' electroencephalography (EEG) activity and overall EEG power. However, caution should be exercised when interpreting "overall" or "complete sleep time" measures since there can be many transient changes that affect the final number. In addition, many studies used white noise in laboratory settings that may not be appropriate for generalization where actual environmental noise may be intermittent or restricted to specific frequency regions. To further complicate things, environmental noise that creates the greatest sleep disruption may have the lowest annoyance compared to other noise stimuli (Elmenhorst et al., 2019).

It is also not clear from the research whether the data can be extrapolated equally to all groups in society. For example, increased age is correlated with increased arousal from sleep due to low-level environmental noise, as are shift workers, especially if alcohol and tobacco are consumed (Pollak, 1991).

In an insightful study, Elmenhorst et al. (2019) examined three environmental noise sources that they considered significantly contributing to general annoyance: air, road, and railway traffic noise. However, these findings may not be transferable to physiological reactions during sleep, decreasing nighttime recovery and mediating long-term adverse health effects. They found that measures of annoyance and studies on sleep awakenings were not always correlated. For example, studies on awakenings from sleep indicate that railway noise, while having the least impact on annoyance, may have the most disturbing properties on sleep compared to aircraft noise. The impact of over 100,000 noise events on assessed awakenings was analyzed in 237 subjects. Results showed that the probability of waking up from equal maximum sound pressure levels (SPL) increased in the following order: *aircraft < road = railway noise*. While the likelihood of wakening from road and railway noise exposure was roughly equal, aircraft noise at 70 dB SPL was 7% less likely to disrupt sleep than the other two noise sources. They concluded that the three major traffic noise sources differ in their impact on sleep. Furthermore, the order with which their impact increased was opposite to what was found in annoyance surveys. They state that “It is thus important to choose the correct concept for noise legislation, i.e., physiological sleep metrics and noise annoyance for nighttime noise protection.” (p. 10).

In an older but nevertheless insightful study, Ando and Hattori (1977) studied the effect of airport noise on unborn fetuses (groups 1, 2, and 3) and newborns (group 4). The environmental noise levels were higher for this study (95 dBA), and there is some question whether these responses are the result of systemic and metabolic changes from the mother or changes directly in the fetus. Babies' reactions to aircraft noise were studied using electroplethysmography (PLG) and EEG. It was found that the babies whose mothers had moved to the area around the Osaka International Airport before conception (group 1) or during the first five months of pregnancy (group 2) showed little or no reaction on PLG and on EEG to aircraft noise. In contrast, babies whose mothers had moved close to the airport during the second half of the pregnancy or after birth (groups 3 or 4) and the babies whose mothers lived in a quiet living area (control group) reacted to the same auditory stimuli. The babies in groups 1 and 2 showed different responses depending on whether the auditory stimuli were aircraft noise or music. “Abnormal PLG and EEG were observed in most babies living in an area where noise levels were over 95 dBA. This suggests that the deep sleep of the babies living in such an area was disturbed, but it is not clear whether there would be any long-term effects from these exposures.” (p. 199).

Amundsen, Klæboe, and Aasvang (2013) describe the Norwegian facade insulation study, which includes modifications to over 2500 dwellings that reduce indoor noise levels. In Norway, about 30% of the population lives near main arterial roads, with in-door noise levels being 55 dBA. In an attempt to remediate this situation, a program was implemented in 2004 and 2005 for more than 2500 dwellings with improved windows, building sound-insulation facades, and in some cases, quieter home ventilation systems. The facade-insulating measures reduced indoor noise levels by 7 dB on average. Before the intervention, 43% of the respondents were highly annoyed by noise. Half a year after the intervention, the proportion of highly annoyed respondents by road traffic noise had been significantly reduced to 15%. In a follow-up study two years later, they found that the number of self-reported annoyances from the outdoor noise level remained lower and that the reduction in the respondents’ self-reported sleep disturbances also remained stable from the first to the second post-intervention study. This suggests that there is some statistical support for this type of assessment. There were no statistically significant differences in annoyance in the control group between the pre-intervention and the two post-intervention studies. This study indicated a reduction from 43 to 15% in annoyance level (on a questionnaire) and was related to a 7 dB noise reduction level.

Smith et al. (2017) evaluated the relative contribution and possible interaction effects of vibration and noise from railways on physiological sleep outcomes. The finding is important that both of these environmental sequalae of railways are important. “Vibration from railway freight often accompanies airborne noise, yet this data is almost totally absent in the existing literature.” (p. 3262). In an experimental investigation, 23 participants, each sleeping for six nights in the laboratory, were exposed to 36 simulated railway freight pass-bys per night with vibration alone, the noise alone (49.8 dBA), or both vibration and noise simultaneously. A fourth exposure night involved 52 pass-bys with concurrent vibration and noise. Sleep was measured with polysomnography. Cardiac activity was measured with electrocardiography. The probability of awakenings was greater following all exposures, including vibration alone, than spontaneous reaction probability ($p < 0.05$). The effects of vibration exposure and noise exposure on changes in sleep stage and arousals were directly additive. This implies that the effects of vibration and the noise were processed separately in the brain, but the mechanism(s) were not investigated in this study. The findings show that vibration and the noise level are important when considering the impact of railway freight on sleep.

Rocha et al. (2019) reported on a survey of sleep disruption for people living near the Atlanta International Airport, and items included questions about sleep quality, sleep disturbance by noise, noise annoyance, coping behaviors, and health. Approximately 10% of over 3000 surveys were returned. Some of the responses were that the calculated outdoor nighttime aircraft noise ("Lnight") was significantly associated with lower sleep quality ($p < 0.05$), trouble falling asleep within 30 min ?1/week ($p < 0.01$), and difficulty sleeping due to awakenings ?1/week ($p < 0.05$). The Lnight level was also associated with increased prevalence of being highly sleep disturbed ($p < 0.0001$) and highly annoyed ($p < 0.0001$) by aircraft noise. The Lnight level was associated with several coping behaviors such as often or always closing their windows ($p < 0.01$), drinking alcohol ($p < 0.05$), using television ($p < 0.05$), and using music ($p < 0.05$) as sleep aids. There was no significant relationship between the Lnight level and self-reported general health or likelihood of a self-reported diagnosis of sleep disorders, heart disease, hypertension, or diabetes.

In another study performed by the same group, Bartels et al. (2021), studied the impact of nighttime (Lnight) road traffic noise, bedroom window orientation, and work-related stress on the subjective sleep quality of almost 4000 working women. Sleep was assessed using a single question on general sleep quality and four questions on specific sleep problems (poor sleep vs. no poor sleep). Work-related stress was assessed by questions about job strain and effort-reward imbalance. Nighttime exposure to road traffic noise was assessed regarding whether the bedroom window faced quiet, medium, or high traffic street noise levels (modelled as <45 dBA, 45-50 dBA, or >50 dBA respectively). Poor sleep was associated with job strain and effort-reward imbalance. The prevalence of poor sleep did not increase with increasing Lnight. Bedroom windows facing a quiet street had a protective effect on sleep in each Lnight category. They found a non-significant trend for an additive interaction between bedroom window Lnight exposure and job strain and concluded that noise levels modelled for the most exposed location likely overestimated the actual exposure and thus may not be a precise predictor of poor sleep. Bedroom window Lnight exposures may be a more relevant factor. Although this did not achieve statistical significance, the authors queried whether potential additive interaction effects between bedroom window orientation and job strain should be considered when interpreting epidemiological study results on noise-induced sleep disturbances.

D: Cognitive/educational issues due to noise:

Unlike the subject areas of the effects of noise on stress and sleep disruptions, the results of low-level environmental noise on cognition and educational/language issues are more straightforward. While it is true that some "well-controlled" laboratory-based studies of the 1960s showed little or no effect, others showed adverse effects on some tasks (e.g., Wyon, 1968 as reported by Bronzaft, 1991). But when switching the research paradigm to a more natural "in situ" setting, more educational measures have achieved statistical significance, especially when other factors such as psycho-social aspects are controlled. It has been argued that the natural settings correlational studies would be better to draw educational and environmental conclusions from rather than (perhaps limited) but well-controlled laboratory studies. (Bronzaft, 1991).

As far back as the early to mid-1970s, studies in a natural environment started to appear. Two, in particular, can be metaphorically referred to as “smoking gun” studies that show precise results. There is, however, no evidence that decreased performance on reading or writing assessments will have any long-term effects.

Cohen, Clark, and Singer (1973) were able to show that children who lived on lower floors of apartments, nearer to noisy expressways, performed poorer on school reading tasks than matched children who lived in higher altitude apartments, farther from environmental noise sources.

Bronzaft and McCarthy (1975) published a study with the telling name “The effect of elevated train noise on reading ability.” The school that was used had half of the classrooms facing noisy train tracks, and the other side of the school was quieter. The students were matched for socio-economic and other factors. During a typical school day, 80 trains passed the school with levels of 89 dBA, and when quiet, the classroom noise levels were 59 dBA. Bronzaft (1991) states that “Students on the noisy side did more poorly on reading achievement tests than did those on the quiet side of the building. The children in the sixth grade who were exposed to the noise were found to be a year behind their counterparts on the quiet side” (p. 88).

Of interest in this last study, noise abatement measures were performed both by the transit authority (rubber vibration isolator pads were installed on the tracks) and the school (acoustic tiling was installed in the noisiest classrooms adjacent to the train tracks), resulting in a 6-8 dB reduction in noise levels. In a follow-up study published 6 years later, after the noise abatement measures were undertaken, the reading levels were assessed for children on both sides of the school and found to be comparable (Bronzaft, 1981).

In the first of four studies by Dockrell and Shield (2004) titled “Children’s perceptions of their acoustic environment at school and at home,” this group assessed the question regarding whether children could be a good judge of the effects of certain environmental noise levels. Over 2000 children completed a questionnaire designed to discriminate different classroom listening conditions, the noise sources heard at home and school, and their annoyance with these noise sources. Teachers also completed a questionnaire about the classroom noise environment. Indeed, children could discriminate between situations with varying amounts and types of noise, and their responses accounted for 45% of the variance in the school environment noise sources. External LAmax levels were a significant factor in reported annoyance, whereas external LA90 and LA99 levels were a significant factor in determining whether or not children hear sound sources. This study demonstrates that children can be sensitive judges of their noise environments and that the impact of different aspects of noise needs to be considered.

In the same year, these same researchers (Shield and Dockrell, 2004) published data on external and internal sound levels in schools in the United Kingdom. Of interest is that they were able to delineate several physical changes (such as window glazing) that could ameliorate the noise levels. They examined 142 primary schools away from airports or airplane flight paths and found that 86% of these schools had outside environmental levels of 57 dBA. The children reported that they were bothered only while performing quieter activities in the classroom and not while the louder activities were being performed. While they did examine the age of the school and factors such as window glazing, their results were inconclusive.

In the third study of their series in the noise and education analysis of primary schools in the United Kingdom, Shield and Dockrell (2008) examined the effects of classroom noise on the academic attainments of primary school children. “External noise was found to have a significant negative impact upon performance in measures of literacy, mathematics, and science; the effect being greater for the older children.” (p. 133). The analysis suggested that children are particularly affected by the noise of individual external events. Other factors that significantly affected the children’s test scores were internal classroom noise levels and background levels primarily related to test results. Even when the data were corrected for social-economic and special needs factors, the negative relationship between performance and noise levels was maintained.

In their fourth and final study in the United Kingdom, this same group studied reading comprehension levels and vocabulary learning tasks in adolescent students (Connolly, Dockrell, Shield, Conetta, Mydlarz, and Cox, 2019). In a study of almost 1000 English high school pupils (564 aged 11 to 13 years and 412 aged 14 to 16 years), reading tasks on laptop computers were completed while the students were exposed to different levels of classroom noise played through headphones. The number of questions attempted, times taken to read the texts and to answer questions were recorded, and correct answers to different types of questions. Two similar experiments were performed with classroom noise at 50 and 70 dB LAeq; and the second at levels of 50 and 64 dB LAeq. The results showed that the performance of all pupils was significantly negatively affected in the 70 dB LAeq condition for the number of questions attempted and the accuracy of answers to factual and word learning questions. However, while the answer was clearer for the younger children and showed statistical significance, it was more difficult to discern whether the effects at 64 dB LAeq, have a detrimental impact on the older pupils.

And finally, as a result of the COVID-19 pandemic, where UNICEF estimates that 1.6 billion children across the world have had their education impacted and have attempted to continue their learning at home, the study by Chere and Kirkham (2021) has some implications for the home-based study and environmental noise levels. 129 students aged 11–18 took part online after passing an online hearing screening test. The students filled out a sociodemographic questionnaire with questions designed to assess their socioeconomic and other factors. This was followed by a home environment and noise questionnaire. Three executive function tasks -the Flanker, the Backward Digit Span, and the Wisconsin Card Sorting Test- were completed while listening to either white noise or a home-like environmental noise. Participants were then stratified into quieter and noisier homes for statistical analyses of the results. Measures of the home environment significantly correlated with individual perceptions of the noise and the task performance. Students in this age group coming from noisier homes were more likely to report that they studied in a noisy room and were annoyed by noise when studying. Regarding noise and task performance, the Flanker task revealed that while the older students in the group were more “efficient” than their younger peers, they appeared to lose that advantage if they lived in noisier homes. Reaction times for younger students from noisier homes were less impacted by accuracy than their peers from quieter homes, though there was no difference for the older adolescents. “This evidence suggests that higher in-home noise levels lead to higher rates of annoyance and maybe hindering home-learning, with both younger and older adolescents being impacted. Furthermore, the long-term effect of in-home noise on adolescent executive function task performance indicates that these findings transcend the pandemic and would influence in-school learning.” (p. 1).

World Health Organization (WHO) Environmental Noise Guidelines for the European Region (2018):

Based on thorough reviews of the available data, the World Health Organization (WHO), (van Kempen et al., 2018) has listed some environmental noise limits where non-auditory systemic effects may begin to be observed. The 2018 WHO document was based on a more recent review of meta-studies and reviews from other sources, and many of the authors of the previous reports contributed to the WHO document. All 9 WHO reports are referenced at the end of this document. The 2018 WHO consensus document was based on 7 systematic studies from 2000 to 2014. Van Kamp et al. (2020) reviewed more recent studies and controlled for confounding and methodological issues from the 2018 review. Among the findings were high-quality studies linking wind turbine noise to sleep alteration patterns, but more study needs to be performed on the long-term effects of environmental noise on cardiovascular dysfunction. Following is a chart, adapted from WHO (2018), summarizing some of the health effects of different average outdoor night noise levels (dB Leq):

< 30 dB Leq	Although individual susceptibilities and circumstances may differ, it appears that up to this level, no substantial biological effects are observed.
30-40 dB Leq	A number of effects on sleep are observed from this range: body movements, awakening, sleep disturbance. The intensity of the effect depends on the nature of the source and the number of the events. Vulnerable groups are more susceptible. A level of 40 dB Leq is equivalent to the lowest observed adverse effect level for night noise.
40-55 dB Leq	Adverse health effects are observed among the exposed population. Many people have to adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.
>55 dB Leq	This situation is considered increasingly dangerous for public health. Adverse health effects occur frequently, a sizeable proportion of the population is highly annoyed and sleep-disturbed. There is some evidence that the risk of cardiovascular disease increases.

Concluding remarks:

A review of the non-auditory effects of lower-level environmental noise on many systems has been reviewed. This is admittedly an extremely difficult area of study with many potentially confounding factors and measures that either have poor test-retest reliability or have a poor correlation with sleep disruption, cognitive and educational issues, stress, and general annoyance. For example, noise that may cause the most significant sleep disruptions may be judged as a noise source associated with relatively little annoyance.

There is also a range of other uncontrolled (or unconsidered) phenomena where some people, in some circumstances and with some types of noise, are more susceptible to its effects. This may be a dose-related effect or even a genetic pre-disposition, … or not- the literature is unclear on this. And to be fair, this same issue of differential “susceptibility” is observed for some sections of the population even for high levels of noise and/or music exposure for measurable and permanent hearing loss, where again, the reasons are not well-known.

There are no “smoking gun” studies or studies that definitively describe predictable and associated effects of low-level noise exposures when taken together. Moreover, while many studies demonstrate changes in some measures, there is no clear evidence that these changes will have long-term consequences.

While it would be tempting to say the sentence "more research needs to be performed," given the inherent difficulties in this area of study, it would be unrealistic to conclude that definitive and predicted results would be able at some point in the near future to be obtained. All that can realistically be said is that for a range of low-level environmental exposures, some people are quite susceptible to its effects, whereas other are not, and that these effects can include sleep disruption, potentially cognitive and educational issues, and an increase in stress and annoyance.

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