What To Do About Environmental Noise?

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The evidence linking environmental noise to negative human health outcomes is increasing. As a pollution problem, is it taken seriously?

Environmental noise is a difficult concept to define. This is due to noise being somewhat subjective to humans depending on their perceptions of specific sounds. We know, for example, that trains, automobiles, and aircraft producing sounds at the same decibel level are all perceived differently when self-reported scores are utilized to assess annoyance for each mode (Lam et al., 2009). There is also evidence that noise from trains is less annoying than noise from aircraft or automobiles. So although definitions can be slippery, they are important nevertheless for placing boundaries around individual concepts, particularly if scholars, acousticians, and policymakers are to understand the nature of environmental noise and its impact on human beings. At a very basic level, definitions determine how noise is assessed, regulated, and mitigated as an environmental problem. Moreover, definitions are crucial if governments, national, and supranational organizations are to work together in a holistic manner to reduce environmental noise in the future.

Environmental noise is any unwanted sound created by human activities that is considered harmful or detrimental to human health and quality of life (Murphy et al., 2009); it results from human interaction with the natural environment. It refers only to noise affecting humans and is typically (but not exclusively) associated with outdoor sound produced by transport, industry, and/or recreational activities. From this definition, it logically follows that environmental noise can be considered a form of pollution. Indeed, its classification as a pollutant is useful because it creates the possibility of confronting noise more intuitively. By definition, pollution is something that is to be avoided, controlled, regulated, or eliminated due to its negative impact on humans and human-environment relationships (Murphy and King, 2014). It is worth noting that although this paper is focused specifically on the impact of environmental noise on humans, many of the issues emerging are relevant and, indeed, instructive for other species (see Hawkins and Popper, 2014). In this regard, there is little doubt that research in human studies may provide guidance for new avenues of research in animals and vice versa.

The relationship between environmental noise and negative human health outcomes is the primary reason that noise is now widely recognized as an environmental pollutant. However, contrary to other pollutants (such as air, odor, and water), environmental noise pollution is, from what we know, not witnessing improvement. Much of this increase in recognition relates to the volume of research that has been undertaken over the last several decades that has improved our understanding of dose-effect relationships for environmental noise and human health. This enhanced understanding between noise and human health has placed noise pollution in the policy limelight, most notably in the European Union (EU). In the United States, there has been much less of a focus, in policy terms, on attempting to assuage the impact of environmental noise on human populations.

Environmental Noise and Health

One of the most important documents to emerge outlining the noise-health relationship in recent years has been *Burden of Disease from Environmental Noise* produced by the European arm of the World Health Organization (WHO; 2011). The document represents the first serious attempt anywhere in the world to examine the evidence base for the noise-health relationship. But it also goes further and produces estimates (for which there is sufficient evidence) of the extent of the disease burden. The calculations utilize data taken from strategic noise maps produced as part of EU member state requirements under the terms of the Environmental Noise Directive (END) that will be discussed briefly in the following section. The WHO (2011) expresses the burden of disease in terms of disability-adjusted life years (DALYs), which is the sum of potential years of life lost due to ill health, disability, or early death and the equivalent years of healthy life lost due to being in a state of poor health or disability (Murphy and King, 2014). Put another way, one DALY is equivalent to an individual losing one year of healthy life.

Table 1 highlights the extent of DALYs lost due to environmental noise exposure in Europe. The main impacts are in terms of annoyance and sleep disturbance, but both are related to other impairments in both adults and children. The five noise-induced exposure impacts referred to cumulatively result in the loss of approximately 805,300 DALYs annually. The WHO study concludes that one in three individuals in Europe is annoyed during the daytime and one in five has disturbed sleep at night purely from traffic noise alone. In cities around the world, it is typically the various forms of transportation that are the main source of environmental noise exposure, with road transport, in particular, being the main offender. In the United States, similar estimates have not been undertaken. However, as far back as 1981, the US Environmental Protection Agency estimated that almost 100 million people in the United States had annual exposure levels to environmental noise that were harmful to human health (Simpson and Bruce, 1981). Despite this, Hammer et al. (2014) note that the US Congress has not seriously discussed environmental noise in more than 30 years. In addition, the recent US study by Swinburn et al. (2015) suggests that reducing environmental noise by a 5-dB A-weighted day-night equivalent level (L_{DN}; the sound level measured over a 24-hour period, with a 10-dB penalty added to the level between 2300 and 0700 hours) would reduce hypertension cases by 1.2 million (1.4%) and chronic heart disease cases by 279,000 (1.8%). Moreover, they estimate the annual associated cost savings and productivity gains in the region of USD 3.9 billion.

Table 1. *Annual burden of disease from environmental noise in Europe*

Noise-Induced Exposure	Public Health Impact
Annoyance	587,000 DALYs lost for inhabitants in towns >50,000 population
Sleep disturbance	90,3000 DALYs for EUR-A inhabitants in towns >50,000 population
Cardiovascular diseases	61,000 years for ischemic heart disease in high-income European countries
Tinnitus	22,000 DALYs for the EUR-A adult population
Cognitive impairment in children	45,000 DALYs for EUR-A countries for children aged 7-19 years

DALYs, disability-adjusted life years; EUR-A, World Health Organization(WHO) epidemiological subregion in Europe comprising Andora, Austria, Belgium, Croatia, Cyprus, the Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Luxembourg, Malta, Monaco, The Netherlands, Norway, Portugal, San Marino, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. Tinnitus is defined as the sensation of sound in the absence of an external sound source (WHO, 2011). Adapted from WHO (2011).

The noise-stress relationship is well understood in principle. Noise activates the sympathetic and endocrine system (Babisch, 2002). Changes in the level of stress hormones are often found in acute and chronic noise experiments: researchers have found increases in the release of stress hormones including catecholamines, adrenaline and noradrenaline, and the corticosteroid cortisol (Babisch, 2003). Moreover, results from laboratory studies have found changes in blood flow, blood pressure, and heart rate in reaction to noise stimuli.

Two principal pathways are outlined in the literature that relate noise exposure to negative health effects (Babisch, 2002). These are the "direct" and "indirect" arousal and activation of the human organism. Direct arousal results from the instantaneous interaction of the acoustic nerve (eighth cranial nerve) with structures of the central nervous system.

However, it is the indirect pathway that is more relevant, and indeed important, for environmental noise exposure. The indirect pathway refers to the cognitive perception of sound, its cortical activation, and related emotional responses whereby both the noise level and the subjective effects of noise annoyance are associated with negative health impacts (Babisch et al., 2013; Murphy and King, 2014). The indirect pathway begins with noise-induced disturbances of activities such as communication or sleep. Indeed, noise induces stress not only by disturbing sleep but also by interfering with relaxation and concentration (and other cognitive functions). The resultant stress activates the sympathetic nervous system and the endocrine system (Babisch et al., 2001). In the laboratory, physiological experiments on humans have shown that noise exposure, even at a moderate level, acts via an indirect pathway and has health outcomes that are similar to those caused by high noise exposures on the direct pathway (WHO, 2009). This is quite remarkable and suggests that even moderate exposure to environmental noise levels is damaging to human health. Moreover, these biological responses to noise during sleep very often go unnoticed by human subjects (Basner and Samel, 2005) but nevertheless may be associated with the aforementioned health impacts.

As mentioned already, annoyance and sleep disturbance are the main impacts of excessive environmental noise exposure and they can lead to or be a trigger for more serious health problems resulting from environmental noise. These relationships are now discussed.

Annoyance

The WHO (2009) concluded that one in three individuals in Europe is annoyed during the daytime while 57 million people (12% of the population) in 25 EU countries are annoyed by road traffic noise; approximately 24 million (42%) of those are thought to be severely annoyed. Moreover, rail traffic noise is estimated to cause annoyance in about 5.5 million people (1% of the European population), 2 million of who are severely annoyed (den Boer and Schroten, 2007). Given the magnitude of the annoyance problem, it is perhaps a little surprising that the relevant authorities and policymakers have not been more active in attempting to alleviate the problems associated with environmental noise exposure (see Rochat and Reiter, 2016).

Noise annoyance is typically associated with the indirect reaction chain in humans that is closely related to the initiation of emotional stress. Indeed, research studies have shown that individuals annoyed by noise tend to experience a series of negative emotions including anger, disappointment, unhappiness, withdrawal, distraction, anxiety, exhaustion, and even depression (WHO, 2011). However, understanding the relationship between environmental noise exposure and annoyance is not a straightforward task. This is largely because the subjective discomfort resulting from environmental noise exposure in humans can be induced by individual perceptions of noisiness, disturbance to daily activities, or a broadly negative feeling about the surrounding acoustic environment. One of the main characteristics affecting an individual's perception of sound as noise is its loudness or perceived intensity (Stansfeld and Matheson, 2003). However, within existing scholarship, the evidence is mixed as to the importance of the duration and frequency components of sound as well as the number of sound events involved in determining annoyance.

Despite this, nonacoustic factors such as age, socioeconomic characteristics, and fear of noise are thought to play a role in determining individual reactions to noise in the form of annoyance scores (Miedema and Vos, 1999, 2003; van Kamp et al., 2004). For example, after controlling for noise level, Fields (1992) found that noise annoyance increases with the fear of danger from the noise source, sensitivity to noise, the belief that the authorities can control the noise, awareness of the nonnoise impacts of the source, and the belief that the noise source is not important. Guaranoni et al. (2012) have suggested that only 33% of noise annoyance is accounted for by acoustic parameters. All off this outlines the importance of gaining a better understanding of human perceptions of environmental sound.

Road traffic noise is responsible for causing the greatest levels of annoyance (WHO, 2009). It has been shown repeatedly in attitudinal studies that the degree of noise annoyance depends on the mode of transport being considered (Miedema, 2004; Lam et al., 2009). At the same average noise level, the percentage of individuals highly annoyed increases as one moves from rail traffic noise to road traffic noise to aircraft noise. This relationship has led to the introduction of a rail bonus in legislation in some countries (e.g., Germany) where limit values for rail traffic noise is 5 dB(A) higher than other traffic modes because of its lesser impact on annoyance (Basner et al., 2011).

Sleep Disturbance

Sleep is an important modulator of hormonal release, glucose regulation, and cardiovascular function. Slow-wave sleep (SWS) is the restorative sleep stage. It is typically associated with decreased heart rate, blood pressure, sympathetic nervous activity, and cerebral glucose utilization when compared with wakefulness (Halperin, 2014). It is during this stage that growth hormone is released and stress hormones are inhibited (Van Cauter et al., 2008). It is now well established in the literature that excessive environmental noise disturbs sleep (WHO, 2011), notably in the form of arousals and awakenings and in reducing the amount of time an individual spends in the deep-sleep stages. These various forms of disturbance are related to health problems including hypertension, heart disease, and cognitive impairment in children (Murphy and King, 2014). Sleep disturbance can be quantified objectively by the number and duration of nocturnal awakenings, the number of sleep stage changes, and modifications in their amounts. Subjectively, it can also be measured through questionnaires distributed to subjects on the morning after a night's sleep (Douglas and Murphy, 2016).

Recent studies focusing on the effects of aircraft noise events on sleep structure have shown that they are associated with a decrease in SWS and increased awakening frequency in study subjects (Basner and Samuel, 2005; Basner et al., 2006). The review by Perron et al. (2012) found a clear association between aircraft noise events and sleep disturbance. The disturbances varied across studies but generally included awakenings, decreased SWS time, and the increased use of sleep medication for noise-exposed subjects. This possible relationship was flagged more than four decades ago when it was reported that rapid eye movement (REM) sleep rhythmicity may also be affected by environmental noise (Naitoh et al., 1975). REM is one of the deep-sleep stages that is important for physical recuperation. Other research by Ohrstrom and Skanberg (2004) has shown that sleep quality at home is reduced after exposure to traffic noise when compared with a quiet reference night.

A study using subjects from Gothenburg, Sweden, analyzed the effects of train noise and vibration on human heart rate during sleep (Croy et al., 2013). The results showed a statistically significant change in the subjects' heart rate within one minute of exposure to train noise and the cardiac responses tended to be higher in the high-vibration than in the low-vibration condition. The results show that the human physiology reacts almost instantly to noise exposure during sleep. In this case, the authors concluded that train noise provokes heart rate accelerations during sleep. Similar results have been found in related studies (Griefahn et al., 2008; Tassi et al., 2010).

Noise-induced sleep disturbance can vary for different modes of transport (road, rail, air) or modes in combination. In a laboratory study in Germany, 72 subjects (32 men) were studied for 11 consecutive nights with 0, 40, 80, and 120 noise events employed in a balanced design in terms of the number of noise events, maximum sound pressure level, and equivalent noise load (Basner et al., 2011). The results revealed that road traffic noise was responsible for the most significant changes in sleep structure and continuity despite the fact that the subjects considered air and rail more disturbing subjectively; cortical and cardiac responses during sleep were lower for air compared with road and rail traffic. An interesting aspect of the study was that the authors asked subjects to complete morning questionnaires to subjectively assess their previous night's sleep. They found that despite subjects being in an unconscious state for most of the night, they were capable of distinguishing not only between nights with and without noise but also between nights with low and high degrees of traffic noise exposure. This and related work (see Douglas and Murphy, 2016) imply that morning questionnaires might be a more robust method of assessing traffic noise effects on sleep than previously thought.

One of the major issues related to environmental noise and sleep disturbance concerns how the noise might be characterized, such as whether the noise is continuous or intermittent. Laboratory studies using recorded intermittent and continuous traffic noise have demonstrated beyond any reasonable doubt that human subjects are more disturbed by intermittent noise than by continuous noise (see Ohrstrom and Rylander, 1982; Murphy and King, 2014). In Ohrstrom and Rylander's study, subjective sleep quality, mood, and performance on reaction time tasks were all impaired by exposure to intermittent environmental noise at night, whereas continuous noise had considerably less impact on sleep quality and no impact at all on mood or task performance. A different study found that intermittent noise with peak levels above 45 dB(A) can increase the time taken to fall asleep by up to 20 minutes (Ohrstrom, 1993). And yet, for public health purposes, noise continues to be evaluated during the nighttime with continuous equivalent noise level indicators such as the sound pressure level in decibels. For example, L_{eq} is equivalent to the total sound energy over a given period of time. In Europe, L_{den} is the A-weighted day-evening-night L_{eq}. It is the noise level measured over a 24-hour period, with a 10-dB penalty added to the level between 2300 and 0700 hours and a 5-dB penalty added to the level between 1900 and 2300 hours. L_{night} is the A-weighted nighttime (2300 to 0700 hours) L_{eq}. L_{den} and L_{night} smooth out intermittent noise events but, more importantly, underestimate the magnitude of the disturbance in favor of the polluter.

In the animal kingdom, there are even more worrying parallels. An important 2005 study tested rats to determine the effect of chronic exposure to environmental noise on sleep and to evaluate the interindividual vulnerability of sleep to environmental noise (Rabat et al., 2005). The study monitored the sleep states of the rats by EEG recording and chronically implanted cortical electrodes. The results of the study demonstrated that after nine days of environmental noise exposure, there was an increase in wakefulness, amounting to 16 hours when compared with a controlled environment of 40 dB(A). In addition, the results showed that exposure disturbed both SWS and paradoxical sleep (PS); after 9 days of exposure, rats lost about 1.1 and 0.75 h/day of SWS and PS, respectively. Perhaps the most interesting results emerging form the research was the revelation that rats do not habituate to their preexposure sleep pattern even after the exposure ends and that chronic exposure to an environmental noise permanently disturbs sleep parameters in rats. The research has potential insights for the relationship between environmental noise and sleep in humans.

The foregoing discussion notes that environmental noise is a significant health stressor that may lead to acute changes in blood pressure and heart rate as well as elevated levels of stress hormones in the body. As a result, the evidence base linking environmental noise exposure and heart disease is increasing. In particular, the evidence demonstrating a link between transportation noise and ischemic heart disease (IHD) has increased considerably (Babisch, 2011, 2014). This is related to evidence that has emerged suggesting that noise exposure increases the risk of hypertension and arteriosclerosis (a thickening or hardening of the arteries). However, the evidence base is considerably stronger for the link with road traffic noise than for aircraft noise. Other studies have examined the relationship between environmental noise and the prevalence of IHD that is generally assessed by cyclical symptoms of angina pectoris, myocardial infarction (MI), or electrocardiogram (ECG) abnormalities or from self-reported questionnaires regarding doctor-diagnosed heart attack (Babisch, 2006). The WHO (2009) has recently concluded that there is sufficient evidence to suggest a relationship between excessive daytime noise exposure and increased cardiovascular risk. The most recent meta-analysis supports a relative 6% increase in IHD per 10-dB L_{den} increase in exposure to transportation noise (Vienneau et al., 2015).

Strategic Noise Mapping

The obvious question to emerge from such a review is, what to do about the problem of environmental noise? The policy and regulatory response to the problem has emerged primarily from Europe through the passing of Directive 2002/49/EC, also known as the END. Article 7(1) of the END requires member states of the EU to produce strategic noise maps for all major roads, railways, airports, and agglomerations on a five-year basis, starting from June 30, 2007. It has resulted in the most comprehensive noise-mapping and population-exposure estimation process in the world.

A standardized schematic of the key steps involved in the strategic noise-mapping process is outlined in **Figure 1**. For the first phase (June 2007), strategic noise maps were compiled for all agglomerations with more than 250,000 inhabitants; all major roads with more than 6 million vehicle passages a year; railways with more than 60,000 train passages a year; and major airports with more than 50,000 movements a year within the territories. The results of this process have recently been made available via a noise observation and information service for Europe (NOISE) that is maintained by the European Environment Agency (EAA; see http://noise.eionet.europa.eu/). A number of scholars undertook an analysis of the finding of the results of the first phase (see van den Berg and Licitra, 2009; Murphy and King, 2014) and outlined significant methodological issues relating to the comparability of results across member states (Murphy and King, 2010). The second phase (June 2012) required that strategic noise maps were produced for all agglomerations with a population in excess of 100,000 individuals and also saw a reduction in the thresholds for major roads (to 3 million vehicle passages) and railways (to 30,000 vehicle passages). The strategic maps must satisfy minimum requirements as listed in Annex IV of the END and should be reviewed every five years.

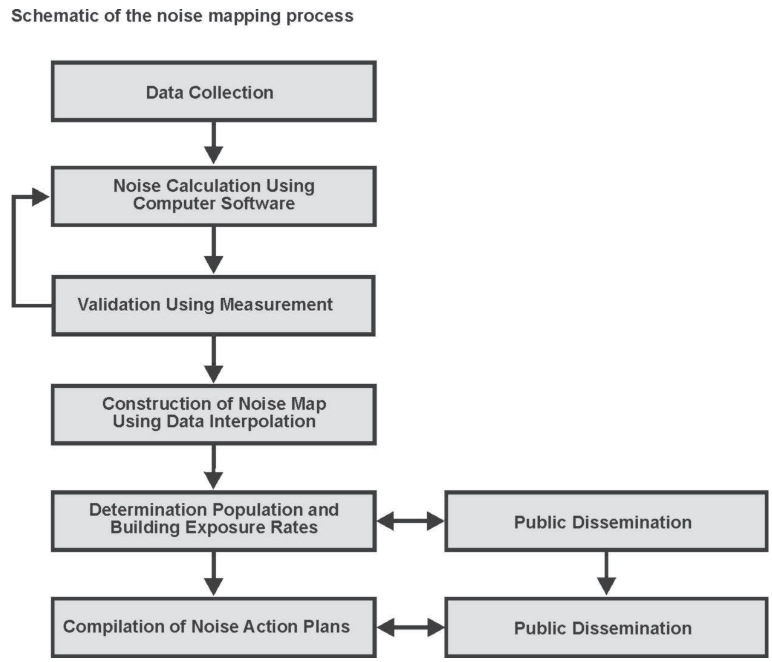

Figure 1. *Schematic of the noise-mapping process.*

In the END, noise mapping is defined as the presentation of data on an existing or predicted noise situation in terms of a noise indicator, noting breaches of any relevant limit value in force, the number of people affected in a certain area, or the number of dwellings exposed to certain values of a noise indicator. From this, it can be seen that under the END, noise maps are considered to be multidimensional because they incorporate not only measured/calculated noise levels for a geographic area but also include information about potential breaches of national statutory limits as well as the number of people and number of dwellings exposed to environmental noise. A strategic noise map has a broader definition within the END as "a map designed for the global assessment of noise exposure in a given area due to different noise sources for overall predictions for such an area" (European Union, 2002). Thus, strategic noise mapping is concerned with the practicalities of the noise-mapping exercise as well as the assessment of exposure within designated areas. Estimates of the population exposed to different noise levels may then be determined from the results of these strategic noise maps. In this regard, the END requires competent authorities in each member state to provide estimates of the number of people living in dwellings in 5-dB bands of L_{den} and L_{night} separately for road, rail, air and industrial sources.

However, the END is not simply a mapping exercise. The Directive also requires member states to determine the levels of population exposure to environmental noise. The relevant authorities must provide estimates of the number of people living in dwellings that are exposed to values of L_{den} and L_{night} in various categories at the most exposed building façade and separately for road, rail, air traffic, and industrial noise. This means that strategic noise maps must be accompanied by relevant assessment data detailing the level of population exposure for the areas being mapped.

Member states are also required to develop noise action plans, which are plans designed to manage noise issues and effects, including noise reduction if necessary (European Union, 2002). Based on noise-mapping results, member states prepare such plans containing measures addressing noise issues (through mitigation measures) and their effects for major roads, railways, airports, and large agglomerations. According to Article 8.1(b), the plans should also aim to protect quiet areas against an increase in noise.

The END also introduces the notion of acoustical planning, which is important for the development of future noise action plans. Acoustical planning refers to "controlling future noise by planned measures such as land-use planning, systems engineering for traffic, traffic planning, abatement by sound-insulation measures, and noise control of sources." In other words, the END implies that national planning systems can be leveraged for the future mitigation of environmental noise; indeed, recent research has demonstrated the impact that land use and traffic management measures, in particular, can have on reducing noise pollution in cities (King et al., 2009, 2011).

However, the END has not been without its critics. Several studies have pointed to important methodological issues that render the comparability of results difficult across member states. The key issues relate to the lack of a standard calculation method as well as the lack of a standard method of estimating population exposure to noise. A recent study analyzing the official results from two phases (in 2007 and 2012) of the process was highly critical of the outcomes (King and Murphy, 2016). It highlighted major discrepancies in reporting between phases 1 and 2, particularly relating to estimates of population exposure. After analyzing the data for the two completed phases, the authors concluded that it is not possible to compare exposure from state to state or draw any real conclusion from [the] published data. Given the issues, they also suggest that it is not yet possible to make an evidence-based assessment as to whether noise exposure is declining or rising across the EU.

The United States

The signing into European law of the END has had a significant policy impact around the world. It has also been important for stimulating noise mapping research that had been fairly scarce until the beginning of the new millennium. Particular areas of research focus have included noise calculation and mapping approaches, methods of assessing population exposure, and different approaches for noise mitigation through noise action planning (Murphy and King, 2014). More broadly, however, the END has had a significant impact in terms of policy transfer throughout the world, with not only scholars but administrative authorities in countries beyond the EU applying strategic noise-mapping approaches to better understand the extent of the noise pollution problem in their territories.

Noise mapping is not mandated in the United States and, as a result, noise-mapping research has been limited. There are, however, a number of academic studies that have taken the EU strategic noise-mapping process and applied it to US locations. To some extent this has been facilitated by European-based commercial noise-mapping software vendors who offer the option to implement the Federal Highway Administration's (FHWA) Traffic Noise Model (TNM) even though it has not been officially "approved" by the FWHA; others have simply applied the EU calculation approaches to locations in the United States that has allowed a number of strategic noise-mapping studies to be undertaken.

Although this is not ideal, it does shine a light on how the process could be useful for US cities. To take a few cases, researchers have created strategic noise maps for roadways in Chittenden County, Vermont (Kaliski et al., 2007). Their work found that 30% of residents were exposed to road traffic noise levels above 45-dB(A) L_{eq} despite Chittenden being considered a rural county in US terms. More recently, Seong et al. (2011) undertook road noise mapping for Fulton County, Georgia, including noise mapping of downtown Atlanta. Their estimates of population exposure from the construction of noise maps found that 48% of the resident population was exposed to noise levels of 55 dB(A) or higher during daytime, with 32% exposed to 50 dB(A) or higher during nighttime. Recent work by King et al. (2014) utilized the noise-mapping process to create a noise map of the city of Hartford, CT, while somewhat related work utilized smartphone noise apps to create a strategic noise map of West Hartford, CT (Murphy and King, 2016a). Larger cities such as San Francisco have also mapped the city's traffic noise levels (Hammer et al., 2014). All of the foregoing demonstrates the possibility of utilizing the EU approach for undertaking strategic noise mapping in US cities.

In the United States, the TNM is the FHWA-accepted calculation method for predicting noise from active highways. It is packaged in the form of an approved computer program, and it is only this program that is validated for use in the United States by the FHWA. Other computer applications can be used to predict noise levels near highways but only if the FHWA has determined that it is consistent with the methodology of the TNM. The TNM was developed primarily to assess the impact of highways and was not meant to be applied to the mapping of complex city environments involving a grid of many receiver points with more reflections and diffraction than would typically be experienced near highways. Because of this, it has not been widely used for noise mapping. In fact, King et al. (2014) assessed the applicability of TNM to mapping studies and found that, in its current form, it is unsuitable for the development of urban noise maps. If the United States is to develop a noise-mapping program in the future, this is a clear obstacle that will need to be addressed as a priority.

The Role of Technology

It is important also to consider the role that smart technology will have in the future monitoring of noise pollution, particularly in cities. The precise role is certainly up for debate, but there seems little doubt that there is likely to be more technology-based passive monitoring of all forms of environmental pollution in the future. With respect to environmental noise, there are two crucial areas of importance. The first relates to the imminent development of electric cars. Given that road traffic noise is the most important source of environmental noise, there is a significant opportunity to reduce pollution and associated health problems through the wider substitution and use of these vehicles over those that are chemically powered. Electric cars are much quieter and so long as the addition of artificial sounds to such vehicles is restricted, they have considerable potential to aid with reductions in annoyance and sleep disturbance. The second relates to the development of low-cost noise measurement devices that are likely to play a greater role in the future. In particular, the development of noise apps for smartphones is likely to become more important as technology improves in the future (see the article by Ben Faber in this issue of *Acoustics Today* for examples).

The technology utilized in mobile/cell phones is Micro-ElectroMechanical Systems (MEMS) microphones that can be constructed relatively cheaply and at a low cost. Indeed, recent research testing smartphones and apps in the laboratory has demonstrated that when a significant number of samples are taken, some of the apps currently on the market are already remarkably reliable if not yet perfect (Murphy and King, 2016b). As the reliability of these microphones improves in the future, they will undoubtedly provide a much better scope for measurement-based noise mapping, something that has already been undertaken in the United States (Murphy and King, 2016a). In addition, low-cost validation of noise modeling results as well as more accurate and reliable once-off measurements may be possible.

More broadly, it is also conceivable that the public could contribute much more significantly than at present in providing noise measurement data through mobile/cell phones in a form of citizen science initiative that could aid noise mapping. This would certainly serve to create a sense of empowerment for citizens with regard to their role in monitoring the quality of their environment.

Biosketch

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References

Babisch, W. (2002). The noise/stress concept, risk assessment and research needs. *Noise and Health* 4, 1-11.

Babisch W. (2003). Stress hormones in the research on cardiovascular effects of noise. *Noise and Health* 5, 1-11.

Babisch, W. (2006). Transportation noise and cardiovascular risk: Updated review and synthesis of epidemiological studies indicate that the evidence has increased. *Noise and Health* 8, 1-29.

Babisch, W. (2011). Cardiovascular effects of noise. *Noise and Health* 13, 201-204.

Babisch, W. (2014). Updated exposure-response relationship between road traffic noise and coronary heart diseases: A meta-analysis. *Noise and Health* 16, 1-9.

Babisch, W., Fromme, H., Beyer A., and Ising, H. (2001). Increased catecholamine levels in urine in subjects exposed to road traffic noise: The role of stress hormones in noise research. *Environment International* 26, 475-481.

Babisch, W., Pershagen, G., Selander, J., Houthuijs, D., Breugelmans, O., Cadum, E., Vigna-Taglianti, F., Katsouyanni, K., Haralabidis, A. S., Dimakopoulou, K., Sourtzi, P., Floud, S., and Hansell, A. L. (2013). Noise annoyance — A modifier of the association between noise level and cardiovascular health? *Science of the Total Environment* 452-453, 50-57.

Basner, M., Müller, U., and Elmenhorst, E.M. (2011). Single and combined effects of air, road, and rail traffic noise on sleep and recuperation. *Sleep* 34, 11-23.

Basner, M., and Samel, A. (2005). Effects of nocturnal aircraft noise on sleep structure. *Somnologie* 9, 84-95.

Basner, M., Samel, A., and Isermann, U. (2006). Aircraft noise effects on sleep: Application of the results of a large polysomnographic field study. *The Journal of the Acoustical Society of America* 119, 2772-2784.

Croy, I., Smith, M. G., and Persson Waye, K. (2013). Effects of train noise and vibration on human heart rate during sleep: an experimental study. *BMJ Open* 3(5): e002655. doi:10.1136/bmjopen-2013-002655.

den Boer, L. C., and Schroten, A. (2007). *Traffic Noise Reduction in Europe*. CE Delft, Delft, The Netherlands.

Douglas, O., and Murphy, E. (2016). Source-based subjective responses to sleep disturbance from transportation noise. *Environment International* 92-93, 450-456.

European Union. (2002). Directive 2002/49/EC of the European parliament and of the council of 25 June 2002 relating to the assessment and management of environmental noise. *Official Journal of the European Communities* L 189, pp. 12-26.

Fields, J. M. (1992). *Effects of Personal and Situational Variables on Noise Annoyance with Special Reference to Implications for En Route Noise*. Report No. FAA-AEE-92-03, Federal Aviation Administration and National Aeronautics and Space Administration, Washington, DC.

Griefahn, B., Bröde, P., Marks, A., and Basner, M. (2008). Autonomic arousals related to traffic noise during sleep. *Sleep* 31, 569-577.

Guarinoni, M., Ganzleben, C., Murphy, E., and Jurkiewicz, K. (2012). *Towards a Comprehensive Noise Strategy*. European Union, Brussels.

Halperin, D. (2014). Environmental noise and sleep disturbances: A threat to health? *Sleep Science* 7, 209-212.

Hammer, M. S., Swinburn, T. K., and Neitzel, R. L. (2014). Environmental noise pollution in the United States: Developing and effective public health response. *Environmental Health Perspectives* 122, 115-119.

Hawkins, A. D., and Popper, A. N. (2014). Assessing the impact of underwater sounds on fishes and other forms of marine life. *Acoustics Today* 10(2), 30-41.

Kaliski, K., Duncan, E., and Cowan, J. (2007). Community and regional noise mapping in the United States. *Sound and Vibration* 41(9), 14-19.

King, E. A., Metcalfe, G., Quitzau, E., and Celmer, R. D. (2014). Towards strategic noise mapping of US cities: A noise map for the city of Hartford, CT. *Inter-Noise and Noise-Con Congress and Conference Proceedings*, NoiseCon14, Fort Lauderdale, FL, pp. 625-632.

King, E. A., and Murphy, E. (2016). Environmental noise — 'Forgotten' or 'ignored' pollutant? *Applied Acoustics* 112, 211-215.

King, E. A., Murphy, E., and MacNabola, A. (2009). Reducing pedestrian exposure to environmental pollutants: A combined noise exposure and air quality analysis approach. *Transportation Research Part D: Transport and Environment* 14, 309-316.

King, E. A., Murphy, E., and Rice, H. J. (2011). Evaluating the impact on noise levels of a ban on private cars in Dublin city centre, Ireland. *Transportation Research Part D: Transport and Environment* 16, 532-539.

Lam, K.-C., Chan, P.-K., Chan, T.-C., Wai-Hong, A., and Hui, W.-C. (2009). Annoyance response to mixed transportation noise in Hong Kong. *Applied Acoustics* 70, 1-10.

Miedema, H. M. (2004). Relationship between exposure to multiple noise sources and noise annoyance. *The Journal of the Acoustical Society of America* 116, 949-957.

Miedema, H. M., and Vos, H. (1999). Demographic and attitudinal factors that modify annoyance from transportation noise. *The Journal of the Acoustical Society of America* 105, 3336-3344.

Miedema, H. M., and Vos, H. (2003). Noise sensitivity and reactions to noise and other environmental conditions. *The Journal of the Acoustical Society of America* 113, 1492-1504.

Murphy, E., and King, E. A. (2010). Strategic environmental noise mapping: Methodological issues concerning the implementation of the EU Environmental Noise Directive and their policy implications. *Environment International* 36, 290-298.

Murphy, E., and King, E. A. (2014). *Environmental Noise Pollution: Noise Mapping, Public Health and Policy*. Elsevier, Boston, MA, and Amsterdam.

Murphy, E., and King, E. A. (2016a). Smartphone-based noise mapping: Integrating sound level meter app data into the strategic noise mapping process. *Science of the Total Environment* 562, 852-859.

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