Sounding the alarm in public health: The case for integrating high quality noise exposure into US health studies

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ABSTRACT

Transportation noise is a significant environmental pollutant routinely overlooked in public health research. This issue is particularly pronounced in the United States, where funding, oversight, and protection have been limited since the defunding of the Environmental Protection Agency Office of Noise Abatement and Control in the 1980s. Despite demonstrated health effects in Europe and globally, most health studies in the United States remain constrained by the absence of detailed community noise assessments, reliable estimates of residential noise levels, and accurate measures of individual-level noise exposures. Despite substantial expertise in epidemiology, spatial science, and acoustical engineering, significant limitations remain in studying the health effects of noise, largely due to the siloed nature of these disciplines in the United States. Here, we examine the challenges of advancing

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public health research on noise pollution, including challenges of convincing stakeholders of its significance, collaborations across disciplines with fundamentally different objectives, and the complexities of developing environmental noise exposure assessments for public health research. We present a forum to foster meaningful collaboration between public health professionals and acousticians.

1. INTRODUCTION

Transportation has been rapidly evolving over the past century, with advancements in technology making it more feasible to build connections across cities, countries, and cultures. While these advancements have greatly enhanced societal mobility, the anthropogenic byproducts of transportation, such as air pollution and noise, pose serious risks to human health. Despite its ubiquitous presence, environmental (transportation) noise has been largely overlooked as a pollutant of public health concern.

In recent years, there has been a call to redefine the term "noise" as unwanted *and/or harmful* sound[1] to better reflect its potential impacts on communities. This has been based on the growing literature highlighting the adverse associations between environmental noise exposure and health, with work mostly conducted in European countries. Over the past decade, the World Health Organization (WHO) European Region has quantified the burden of disease attributable to environmental noise in European countries to be at least one million disability-adjusted life years (DALYs) annually.[2] While considerable efforts have been made in Europe to address and mitigate the impacts of transportation noise on health, less has been done to quantify and address the health burden of noise in the United States (US), despite the longstanding concerns from communities around the country. The field of acoustics in the US has seen substantial growth, contributing to the design of quieter aircraft, road vehicles, and infrastructure as well as providing state-of-the-art techniques to aid federal and state transportation projects and in decision-making. However, the intersection of public health and acoustics has not received the same level of attention as other intersecting environmental issues.

In this paper, we provide an overview of noise and health research, outlining the rationale for examining noise effects beyond annoyance, as well as the current state of the epidemiologic evidence. Providing this background will set the foundations for further discussion of the challenges of advancing this work to inform policy and intervention. Key barriers to this work include convincing stakeholders of the significance of noise health effects, collaborating across disciplines with varying objectives - particularly recognizing that the authors of this paper are primarily from the public health field - and developing exposure assessment techniques appropriate for studying noise-health associations. Although rail noise exposure and noise in occupational settings present many important issues to communities, this paper will focus mainly on aircraft and road traffic as sources of transportation and community noise in the residential setting.

2. NOISE AND HEALTH RESEARCH

2.1. Proposed mechanisms relating noise to health

The health effects of noise have been documented over centuries, with one of the first calls to public health action communicated by scientists and physicians to the American Public Health Association in the 1890s.[3] Over time, researchers have studied and refined proposed biological mechanisms linking noise to adverse health outcomes through physical functional and psychological stress responses.[4–12] A key purpose of the human auditory system is to process sound relative to survival, and there may not be a complete adaptation to the constant exposure to modern noise sources.[6] Additionally, noise can be subjectively and objectively stressful and subsequently harmful even if not perceived,[6] demonstrating that noise is not merely a nuisance. Broadly, chronic noise exposure can lead to disturbances in sleep, communication, and cognitive and emotional states. These changes can induce stress-related responses with early manifestation of disease risk, such as hypertension and diabetes.

Such biological reactions from noise occur when sound waves in the form of pressure vibrations convert into nerve impulses within the ear.[13] These impulses can trigger a cascade of neurohormonal processes, which in turn activates the "fight or flight" and "defeat" responses through secretion of stress hormones and mobilization of glucose and fatty acids into the blood stream to provide energy to central organs, such as the brain and heart.[6,13] Studies have shown that chronic exposure to these stress hormones can result in vascular oxidative stress and dysfunction, increased blood pressure, and atherosclerotic changes in blood vessels.[7,9,13–18]

Among the multiple pathways of noise leading to biological dysfunction, sleep disruption plays a predominant role. Many studies have linked increasing noise exposure with reduced sleep quantity,[12,19–21] more frequent awakenings and changes in sleep stages,[19,22–24] and overall sleep efficiency/quality.[20,21,25–29] Deficiencies in sleep characteristics can result in elevated concentrations of stress hormones;[19,30] inflammation, oxidative stress, and endothelial dysfunction;[7,9] disruption of circadian rhythm;[7,19] in addition to daytime tiredness.[19] Chronic sleep deficiencies and subsequent chronic upregulation of physiological and psychological stress further lead to adverse disease endpoints, as discussed earlier.[31] Sleep is essential for physical and cognitive restoration, so that disruptions in sleep-wake cycles are related to subsequent neurodegenerative changes and the progression of neurodegenerative diseases.[32–37] In particular, uninterrupted sleep plays a role in establishing stable function of the body's glymphatic system, which clears biological waste products from the brain.[32,33,35,37]

Experimental and human studies suggest that chronic exposure to environmental noise may elicit cardiovascular and neurological disease through additional pathways.[38,39] For example, glucocorticoids like cortisol can affect blood glucose levels by inhibiting insulin secretion.[40] An animal study examining the effects of chronic noise exposure found increased blood glucose levels with decreased insulin sensitivity in rats exposed to noise over 28 days compared to controls.[40] Additionally, a biomedical imaging study examining noise exposure among 498 healthy adults found mediating associations between noise and major adverse cardiovascular events (MACEs) such as myocardial infarction (MI) through increased amygdala activity and arterial inflammation.[16]

2.2. State of the current epidemiological literature

Although biologically plausible, epidemiological studies have provided inconsistent results in understanding the potential magnitude of effect between environmental noise and health outcomes, particularly in relation to cardiometabolic and neuropsychiatric outcomes. Much of the existing research has been conducted in Europe, often designing cohort studies for sampling from communities with large exposure heterogeneity. For example, the Hypertension and Environmental Noise near Airports (HYENA) study examined associations between aircraft and road traffic noise with cardiometabolic outcomes across seven European airports, reporting moderately-sized associations, particularly with night-time measures suggesting mechanistic pathways relating to sleep disturbance.[41,42] Studies have reported a wide range of effect estimates, prompting multiple systematic reviews and meta-analyses to synthesize findings. Notably, a recent Umbrella+ report from the European Environment Agency conducted a "review of reviews," integrating evidence from systematic reviews and high-quality original studies since 2015.[43] The authors reported a 4.1% (95% confidence interval [CI]: 1.4, 6.9) increase in all-cause mortality per 10 A-weighted decibel (dBA) increase in day-evening-night average sound level (L_{DEN}) across all transportation sources; among road noise only, the risk of all-cause mortality was 5.5% (95% CI: 2.6, 8.4).[44] In terms of hypertension, the estimated increased risk was 4.7% (95% CI: 0.5, 9.2) per 10 dBA from all transportation noise sources, though estimates for road and aircraft noise had wider confidence intervals, with increased risks of 4.5% (95% CI: -3.0, 12.6) and 8.1% (95% CI: -2.3, 19.9), respectively.[44] It is important to note that the lack of statistical significance does not imply the lack of an association; statistical significance conflates magnitude with precision, as there may be a lack of heterogeneity among the exposure and/or cases, or a critical modeling assumption may be violated.

In the US, there has been a limited number of studies conducted on the non-auditory health effects of transportation noise; yet in recent years, the number of studies has noticeably increased. Studies have been conducted in cohort studies and large electronic medical record databases examining a number of different outcomes, such as cardiovascular and metabolic disease,[16,28,45–51] sleep,[12,23,28] cognition,[52–54] mental health,[55] and mortality.[49] Results of these studies have been mixed, with most showing effect estimates of modest magnitude. For example, a study based on Medicare data showed associations between increasing levels of aircraft noise and cardiovascular-related hospitalization admission rates at the zip code level among six million participants surrounding 89 airports resulted in an increased rate of cardiovascular hospitalization of 3.5% (95% CI: 0.2, 7.0) in rates per 10 dBA of aircraft noise exposure.[46] Road noise exposure has also been associated with an estimated 20% increased risk of cognitive impairment (HR: 1.20; 95% CI: 0.95, 1.50) in a California community of adults.[53] Overall, the epidemiologic literature has made strides in examining the relationships between environmental noise and health; given the shift of both the US and global demographics to older populations, more focus is currently being made to understand the drivers of dementia and other diseases related to aging, which include focus on environmental determinants, such as transportation noise.

3. CHALLENGES OF ADVANCING PUBLIC HEALTH RESEARCH ON NOISE POLLUTION

3.1. Challenges of convincing stakeholders of its significance

Despite growing evidence of the potential health impacts of environmental noise, there has been limited legislative movement in the US since the 1980s. This has been a result of multiple factors, including the absence of federal-level funding of noise initiatives; fragmentation of coordinated efforts across federal, state, and local agencies; and lack of visibility, urgency, and understanding of the effects of noise on health.

In the 1970s, Congress passed several key pieces of legislation aimed at addressing environmental noise: Title IV of the Clean Air Act of 1970, the Noise Control Act of 1972, and the Quiet Communities Act of 1978.[56–59] Under these laws, the US Environmental Protection Agency (EPA) had the authority to direct noise research and control initiatives through the Office of Noise Abatement and Control (ONAC).[56–58] Additionally, these laws empowered and funded the EPA to assist state and local governments with implementing noise control grant programs and providing technical assistance through the Quiet Communities Program.[59,60] In 1981, the Office of Management and Budget directed the EPA to transfer noise control responsibilities to state and local governments, which led to the defunding and closure of ONAC, as the Federal Administration during this period viewed noise as a localized issue.[57,60] Although the EPA lost its capacity to enforce or advance noise initiatives, the legislation giving EPA legal responsibility for regulating noise (Title IV of the Clean Air Act, the Noise Control Act, and Quiet Communities Act) was never repealed.[60] As a result, many state and local agencies deprioritized noise in favor of other pressing issues, citing that regulation was a federal responsibility despite the lack of federal funding.[60] This lack of coordination between federal, state, and local authorities led to a significant decrease in state and local noise regulation and control.

Although not required, different federal agencies have also developed guidance to state and local agencies to address and mitigate noise exposure; however, this guidance is mostly out-of-date and does not include updated knowledge on the effects of noise on health. For example, the Federal Aviation Administration (FAA) uses a DNL threshold of 65-75 dBA to denote "significant" and ≥75 dBA as "severe" levels of aircraft noise to determine eligibility for noise abatement and residential land use compatibility assessments, based on community surveys of annoyance from the 1970s and revalidation in the 1990s.[61,62] The Federal Highway Administration (FHWA) primarily uses a threshold of 67 dBA for sound levels exceeded 10% of the time (L_{10}) for noise abatement based on a 1974 document (known as the *Levels Document*).[63,64] These metrics and threshold values differ from what has been recommended by the WHO European Region in 2018, which proposed aircraft noise levels thresholds of 45 dBA and 40 dBA for L_{DEN} and night-time noise (L_{NIGHT}), and road noise level thresholds of 53 dBA and 45 dBA for L_{DEN} and L_{NIGHT}, respectively.[65]

The absence of noise policies and initiatives at the federal level has been deepened by the limited public and political awareness of the environmental noise impacts on health. Unlike more visible or acute environmental threats, such as wildfires or chemical spills directly contributing to air and water pollution, noise pollution has been often difficult for individuals who are not directly affected to conceptualize noise as an urgent public health issue.[60] As a result, noise is frequently dismissed as a mere nuisance or inconvenience rather than an environmental toxicant capable of resulting in adverse health effects. The historical minimization of noise-induced health effects, such as annoyance, may parallel the historic societal trends in the trivialization of mental health.[66–69] However, as mental health awareness has become more accepted and less stigmatizing over time, there may be growing recognition of the cumulative impacts of noise on psychological and physiological well-being.

3.2. Complexities of developing environmental noise exposure assessments for public health research

Developing environmental noise exposure assessments for public health research presents various challenges, largely due to the complexity of data and resources needed to obtain individual-level residential noise measurements. Given the high costs in time, money, and resources to measure individual-level long-term continuous sound levels, most noise estimates are generated based on noise prediction models, specifically through noise propagation methods. Broadly, these models estimate the sound power level generated at sources of the sound and then incorporate the physical phenomena of how sound waves travel from the source to an individual receiver, accounting for attenuation parameters, such as geometric spreading, ground effects, atmospheric absorption, and diffraction.[70] Mathematical models can incorporate more comprehensive data to generate estimates at finer spatial and temporal resolutions depending on the source and the noise metric needed (e.g., L_{DEN}, L_{10}, L_{NIGHT}).

Despite these advancements, the field of public health in the US has yet to develop comprehensive, fine-resolution national noise models comparable to models used for air pollutants, such as fine particulate matter. In many cases, public health researchers rely on land-use regression (LUR) models that predict time-invariant estimates of environmental noise from land-use, environmental, and traffic-related characteristics, such as traffic volume, population density, and proximity to transportation sources. These models require less computational power and can be built with more readily available geospatial data, especially when detailed noise source input data are not readily accessible. LUR models also have the potential to estimate the total exposure of environmental noise regardless of the source, as they use a subsample of sound measurements taken over an area to train predictive surfaces across area and time. However, little has been done to rigorously compare performances of LUR models to propagation methods across various frequency ranges or environments.[71] There also are challenges in obtaining data for LURs to estimate time-specific estimates (e.g., L_{NIGHT}) that may be more biologically relevant. Moreover, potential biases may arise in health analyses if predictors of the noise models acting as proxies for confounding variables are added to health models (e.g., population density).[72]

Regardless of the model type, noise models require specific and comprehensive inputs that may not be readily available or have historically been included in the modeling process. Localized data on how noise travels to residential spaces based on building height or at façades has become vital for noise and health associations.[73] The spatial resolution of available input data may be too coarse to capture fine-resolution variation in exposure, raising concerns related to the modifiable area unit problem (MAUP).[74,75] Lastly, comprehensive traffic-related inputs, such as traffic volume, have been difficult to obtain historically (pre-2000s), particularly as state agencies were left responsible to capture these data. As noise is a highly spatially heterogenous environmental phenomenon,[73] there must be careful consideration of the spatiotemporal resolution to avoid exposure misclassification.

3.3. Collaborations across disciplines with fundamentally different objectives

Many of the methods used in public health noise exposure assessment originate from acoustics, where the primary focus is often on the complex dynamics of sound and regulatory compliance (e.g., Environmental Impact Statements for road noise, Part 150 Noise Compatibility studies for aircraft noise).[76] This focus has led to the development of sophisticated computational tools, such as Traffic Noise Model (TNM), CadnaA, and SoundPLAN, that can simulate sound propagation using large amounts of complex inputs, including topography, meteorology, and obstacles that may affect sound waves from traveling from a source to a receiver. While these tools are highly effective for engineering and regulatory applications, they were not designed to assess the impacts of noise on human health or to model individual-level residential noise exposure. For example, state transportation agencies typically use these models to estimate road traffic noise under steady-state conditions along major highways to meet environmental regulatory compliance requirements. In contrast, public health researchers require a more comprehensive look at noise that accounts for all traffic types along any roadway, including local or minor roads that may be closer to residential areas as these exposures would be more relevant to chronic noise exposure. The limited collaboration between the acoustics and public health fields has been compounded by insufficient funding for noise and health research; without the necessary funding for these projects, collaborations are unlikely to exist, as acousticians and public health researchers lack the protected time necessary to engage in cross-disciplinary work.

4. CONCLUSIONS

Although the current regulatory landscape involving noise is fragmented, outdated, and under-resourced, there is building momentum for renewed federal leadership, cross-sector collaboration, and scientific investment. Currently, the FAA is conducting a noise policy review, addressing public comments, and partnering with academic institutions and community groups to investigate the impacts of noise on health, with the understanding of the gap in US research and policy.[77] Additionally, in 2023, a bill was introduced for EPA to re-establish ONAC and re-fund noise research and control to support state and local agencies;[78] and in 2024, a non-profit noise advocacy organization filed a lawsuit against the EPA for neglecting to address noise concerns of communities.[79] While it remains uncertain how these developments will unfold given the current increase environmental de-regulation, these developments reflect a growing recognition that noise is not merely a nuisance but a legitimate public health concern.

To advance noise policy, the development of high spatiotemporal resolution predictive noise models will be essential. These tools will be critical for identifying high-impact communities that receive the highest burden. When aligned with community input, noise estimates from these predictive models will help researchers and communities understand what research questions to ask and what targeted policies, interventions, and solutions are needed to effectively mitigate noise. Providing access to current noise maps would facilitate a good first step.[80]

Achieving these goals will require coordination between federal, state, and local agencies, academia, and private industry/consulting. Future regulatory and research efforts should incorporate lessons learned from the international to local area context, understanding the benefits and barriers to implementing mitigation strategies and finding reasonable compromises.

As our populations are shifting to an older, more diverse demographic, the urgency to understand and mitigate environmental determinants of chronic diseases (e.g., dementia, cardiovascular disease) will only increase. Proactive investments in noise research, monitoring, and regulation can play a pivotal role in reducing the long-term burden of disease and improving population health.

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