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Editorial

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The effects on sleep play a critical role in the long-term health consequences of noise exposure

Mathias Basner[1,*] and Michael G. Smith[2]

[1]Unit for Experimental Psychiatry, Division of Sleep and Chronobiology, Department of Psychiatry, University of Pennsylvania Perelman School of Medicine, Philadelphia, PA, USA and
[2]School of Public Health and Community Medicine, Institute of Medicine, Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden

[*]Corresponding author. Mathias Basner, Unit for Experimental Psychiatry, Division of Sleep and Chronobiology, Department of Psychiatry, University of Pennsylvania Perelman School of Medicine, Philadelphia, PA, USA. Email: basner@pennmedicine.upenn.edu.

Sleep is a very dangerous state from an evolutionary perspective as we are unconscious and it takes time to arouse from sleep and react to threats in a meaningful way. Thus, it is not surprising that our full sensory array continues to monitor our environment during sleep, always ready to wake us up (although with different sensitivity depending on sleep stage). In fact, the multiple brief awakenings a healthy sleeper experiences during the night [1] can be thought of as "brief checks" into our sleep environment. As a long-range sensor, the auditory system plays a critical role in monitoring the environment during sleep. It analyzes not only sound levels but also sound content during sleep [2]. The thalamus has a gating function, shielding the cortex from sensory content deemed irrelevant, often associated with a K-complex in the electroencephalogram [3]. We do habituate to noise, but still react to individual noise events during sleep even after long exposure periods (i.e. years), albeit with lower probabilities. Compared to cortical arousals, autonomic arousals habituate to a much lesser degree with likely implications for long-term health consequences (see below) [4].

While the watchman function of the auditory system has served us well on our evolutionary journey, it is less relevant in modern societies where humans sleep in solid housing structures, safe from predators. However, there is no way to switch off biology that has evolved over millennia. Countless studies have unequivocally shown that exposure to traffic noise disturbs sleep and impairs sleep recuperation, without posing any obvious threat [5, 6]. Sensitivity to noise-induced sleep disturbance varies substantially inter-individually [7]. Interestingly, there seems to be a "sweet spot" for the propensity to arouse to internal or external stimuli, with mortality increasing for both very low (e.g. more severe oxygen desaturations in OSA patients?) and very high (e.g. higher degree of noise-induced sleep disturbance?) propensities [8].

At the same time, numerous epidemiological studies have demonstrated associations between environmental noise exposure and long-term health consequences, including cardiovascular disease [9], diabetes [10], cancer [11], and neurodegenerative disease [12]. It is likely no coincidence that short or low-quality sleep has been associated with the same disease endpoints. Recent animal research suggests that intermittent noise exposure during the night is the culprit for the pathophysiological changes that predispose to negative health consequences, while continuous noise exposure or exposure during the day elicited no or much smaller effects [13]. The observed changes include oxidative stress-induced vascular and brain damage, uncoupling of endothelial and neuronal nitric oxide synthase, vascular/brain infiltration with inflammatory cells, and changes in circadian rhythms [14], which all provide biologic plausibility for the associations observed in epidemiological studies. Endothelial dysfunction was also found in human participants after a single night of noise exposure [15], with stronger effects in patients with preexisting cardiovascular conditions [16], and partially mediated by Vitamin C application indicating the involvement of reactive oxygen species in causing vascular dysfunction. Aircraft noise can also trigger acute cardiac events during sleep which constitutes another mechanism of how noise exposure can contribute to cardiovascular mortality [17].

In a Perspectives piece published in this issue of *SLEEP* [18], Ellenbogen et al. discuss the effects of wind turbine noise on sleep, and they do a remarkable job in making their text accessible to laypeople including engineers with limited knowledge of sleep and sleep researchers with limited knowledge on sound measurement and prediction. Noise is defined as unwanted and/or harmful sound [19], stressing that both sound perception and the degree of control over the noise source can affect the reaction to noise. It is thus no surprise that an emotional response to noise mediated by the Amygdala likely plays a key role in major adverse cardiovascular events [20]. The societal discourse about noise is equally emotional, stressing the importance of noise-effects research as a "fact-deliverer" that can inform political and legislative decision-making. The latter is not an easy task and a balancing act, as a noise source typically also generates benefits for a group of individuals or society at large. For example, while aircraft generate noise, airports and airlines also create jobs and revenue, and for many it is very convenient to live close to an airport. Likewise, clean energy produced by wind turbines is critical in the fight against climate change.

Ellenbogen et al. [18] perform a narrative review of recent studies on the effects of wind turbine noise on sleep and suggest that "noise from wind turbines measured outside the residence, up to 46 dBA (or modeled up to 49 dBA using the new standard), poses no risk to human sleep." One wonders how this suggestion compares to existing "official" limit values? Limits exist in many countries and provinces worldwide, for example, 37-44 dBA in Denmark, 45 dBA in Victoria, Australia, and 40-51 dBA in Ontario, Canada. These limits are often contingent on wind speed, with limits allowing for higher noise levels at higher speeds, and also the area in which wind turbines are sited, with limits demanding lower noise levels in quiet rural areas and areas which are primarily residential compared with more industrial or urban locations. In the United States, however, limits for wind turbine noise do not exist, at least not at the federal level. The Noise Control Act of 1972 (42 U.S.C. § 4901) is supposed to protect Americans from noise that jeopardizes their health and welfare. However, the Office of Noise Abatement and Control at the Environmental Protection Agency was defunded by the Reagan administration in 1982 and continues to be without funding. Since then federal guidance in developing, funding, disseminating, and coordinating information about the serious health impacts of noise has been imperceptible despite a continued congressional mandate. This includes the mandate to "conduct or finance research [. . .] on the effects, measurement, and control of noise, including but not limited to [. . .] investigation of the psychological and physiological effects of noise on humans [. . .] and the determination of dose/response relationships suitable for use in decision making, with special emphasis on the nonauditory effects" (quoted from the Noise Control Act). These dose/response relationships have mostly been generated in Europe and Asia, although other U.S. federal agencies have started to step in (e.g. [21]). Noise policy should be reviewed on a regular basis, include a review of the current literature and various stakeholders (i.e. those affected by noise, those generating noise, health organizations, researchers, and federal agencies). This is even more important as noise is also a justice and equity issue, disproportionally burdening underserved and low-income groups.

The importance of the environment for sleep quality cannot be overstated. In addition to noise, other factors like temperature and air quality play important roles [22]. Studies that inform health impact assessments are critically needed, but we also need to better understand whether noise mitigation strategies work. Noise reduction at the source is the best way of addressing noise effects, but it is sometimes either technically infeasible or too expensive. We therefore need to understand whether simpler and less expensive noise mitigation measures (e.g. sound insulation, white noise [23], and earplugs) are effective in reducing the effects of noise on sleep. Ellenbogen et al. [18] are to be commended for communicating a complex issue to a lay audience, sleep researchers, and engineers alike, and offering a limited value for further discussion.

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