Public Exposure to Airborne Ultrasound and Very High Frequency Sound

Timothy G. Leighton, Ben Lineton, Craig Dolder, and Mark D. Fletcher

Over the last decade, members of the public have complained of "high-pitched" sounds in public places causing adverse effects (e.g., headaches). Their reports were dismissed by colleagues, family, and friends, who could hear nothing, and by health care professionals and experts for a range of reasons, including assertions that airborne ultrasound could not affect humans because it mostly reflects off the skin and because the ultrasonic intensities in air are low. Those complaining were told that even if such sounds existed, the sounds could not be ultrasonic because "humans cannot hear above 20 kHz." Faced with universal dismissals, in 2015, the concerned individuals consulted one of the authors, Professor Leighton. He published evidence that such tones existed (Leighton, 2016a), provided methods for the public to detect them (Leighton, 2016a,b), identified a range of commercially available sources and others in development, outlined why the regulatory framework needed revisiting (Leighton, 2016a), and cast doubt on assertions that these high-frequency sources cannot cause adverse effects (Leighton 2017). Fletcher et al. (2018a,b) conducted human trials and interest grew around the world, including in a special issue in *The Journal of the Acoustical Society of America* (Leighton, 2018). International interest in this topic further increased with claims of ultrasonic attacks on the Cuban embassy (Leighton, 2018). A scheme by which the public can distinguish such tones from, say, tinnitus was provided, as illustrated in the following case study.

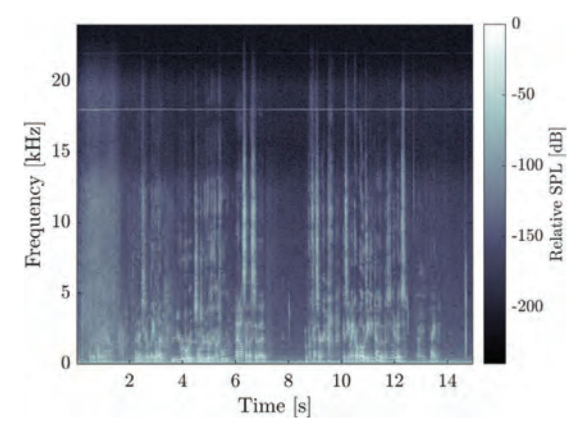
A Case Study

On September 14, 2019, Jill Zawatski, a teacher from the Seattle (WA) area, wrote to Leighton because her students aged 14-18 claimed that a "high-pitched" sound in the classroom gave them headaches. School administration, teachers, and maintenance workers could hear nothing, but Mrs. Zawatski had come across Leighton's work and understood from it that there was a huge variation in the sensitivity of human hearing to high frequencies and, probably, to being adversely affected by high-frequency sound.

On receiving her e-mail, Leighton explained that the first step is to distinguish the perceived sound from tinnitus by (1) testing whether the sound is reduced when wearing ear protection or when moving to another location; and (2) attempting to detect the sound using a smartphone once the settings have been appropriately adjusted (the upper frequency limitation, 24 kHz, is determined by the data acquisition and not the microphone; Leighton, 2016a,b).

Mrs. Zawatski promptly recorded an audio file showing a tone at 18 kHz (see **Figure 1**). This frequency is covered by ultrasonic regulations because the dozens of national and international bodies (Leighton, 2016a) setting guidelines for ultrasonic exposure have, by using third-octave

Figure 1. *Time-frequency analysis of the recorded audio file showing a steady tone at just over 18 kHz in the classroom. SPL, sound pressure level.*



https://doi.org/10.1121/AT.2020.16.3.17

bands (TOBs), set the same maximum permissible levels (MPLs) for 17.8-22.4 kHz (the TOB centered on 20 kHz; Leighton, 2017, 2018). This is a difficult band in which to set MPLs because of the huge spread in hearing threshold level (HTL; the lowest detectable sound pressure level [SPL] of a pure tone) across listeners. That spread is 85 dB between the 5th and 95th percentile HTLs at 20 kHz for 20-29 year olds (Rodríguez Valiente et al., 2014). Indeed, Ashihara et al. (2006) recorded pure-tone HTLs at 24 kHz as low as 88 dB SPL (all SPLs in this article are Z-weighted and expressed in dB re 20 μPa). Here, we define three frequency regions for humans delimited by TOB boundaries, specifically, the lower audio frequency range below 11.2 kHz, the very high frequency sonic (VHFS) range from 11.2 to 17.8 kHz, and the ultrasonic range above 17.8 kHz (Leighton, 2017).

After receiving Figure 1 from Leighton, Mrs. Zawatski told him:

"Two school district maintenance men came to help. They had heard of another case of this at a different school in the district — the sound was driving the (younger) teacher crazy but they were unable to hear it. I downloaded the app on their phones, adjusted the factory settings, and they went to work. Within short order, they had climbed onto a ladder and discovered the source of the sound. It was a defective motion sensor for the classroom lights that was supposed to be functioning at 40 kHz. They removed the motion sensor and problem solved. The students could immediately tell the difference (of course) and they were so happy and relieved."

The Context of This Case Study

Because the SPLs displayed by smartphone apps are not reliable, it was impossible for Leighton to compare the recorded level in the WAV file used for **Figure 1** with the recommended MPLs for this public exposure published by the International (including the United States) Commission on Non-Ionizing Radiation Protection (ICNIRP; INIRC-IRPA, 1984). For tonal outputs in the range from 17.8 to 22.4 kHz (20-kHz TOB), the MPL is 70 dB SPL. Public exposures should never be authorized by comparison with MPLs for occupational exposures where knowledge of the age, preexisting conditions, hearing protection and health degradation of the subject, and duration and location of the exposures, allow supervision. The ICNIRP's public exposure MPLs allow no amplitude/duration trade-off.

It would have been illuminating to discover whether the SPL of the sound recorded in **Figure 1** exceeded the 70 dB MPL. If the SPL of this motion sensor exceeded 70 dB, it would indicate a need for greater vigilance in the signal levels that commercial equipment can generate in classrooms. However, if the SPL was less than 70 dB, it would indicate that these interim MPLs are inadequate to protect young people. This may be the case, given that the ICNIRP's public MPLs were based on subtracting 30 dB from occupational MPLs that, in turn, were based on tests of a small number of adults. If 70 dB had indeed been causing an adverse reaction in Mrs. Zawalski's classroom, it may appear surprising that such low levels might generate headaches. However, if one can hear ultrasonic frequencies, the usable dynamic range (between what is perceptible and what causes adverse effects) is likely to be unexpectedly small in many individuals (Leighton, 2017).

What Is Known About Ultrasonic Effects on Humans?

Past questions of adverse effects from airborne ultrasound had focused on measurable changes in HTLs as a result of occupational exposures, either as temporary or permanent hearing threshold shifts (TTSs and PTSs, respectively). However, this article is concerned with public exposures where, to date, the SPLs have tended to be low enough that TTS and PTS are unlikely. Consequently, our focus is on adverse effects provoked at these lower SPLs, including (but not limited to) discomfort, failure to concentrate or perform tasks, tinnitus, nausea, dizziness, and a feeling of pressure in the ear. Unlike PTS, these symptoms do not necessarily indicate hearing damage but may arise from brain responses to an audible stimulus.

However, persistent exposure could conceivably cause similar health effects (e.g., sleep deprivation and cardiovascular disorders) to those associated with environmental noise exposure at lower audio frequencies (Murphy, 2017). Most claims of adverse effects of airborne VHFS and ultrasound on humans are anecdotal. This is because controlled experiments and epidemiological studies of chronic exposure are rarely funded, and when they are, they are difficult to conduct. For decades, ultrasonic pest deterrents and cleaning baths exposed humans to ultrasound in the air, and a plethora of national and international guidelines for MPLs for occupational exposure was produced (Leighton, 2016a). These tended to recommend SPLs of 110 dB for the TOBs

Table 1. *Examples of incidental or deliberate exposures from commercial devices*

Incidental or Deliberate Exposure?	Commercial Source	Frequency	SPL Levels at the Possible Position of the Human Ear	Reference for Measurement
Deliberate	Pest deterrents: Used to deter birds, rodents, and insects away from locations (barns, homes, and shops)	20-kHz TOB	130 dB at 1.6 m 90 dB at 14 m	Ueda et al., 2014a,b
			92 dB at 1.7 m	Dolder et al., 2018
Deliberate	Teen deterrent: Exploits high-frequency sensitivity of teenagers and children to deter them from shops as age-discriminatory deterrent to make the shop more welcoming to older customers who are assumed to have greater purchasing power and be less likely to steal.	12.5-kHz TOB	72 dB at 1.5 m	Conein, 2006
		16-kHz TOB	92 dB at 1.5 m	
		20-kHz TOB	80 dB at 1.5 m	
Incidental	Public-Address-Voice-Alarm: Speakers, usually set in ceilings or high on walls in public places to alert people, e.g., to evacuate in case of bomb threat or fire; by EU law must be monitored to ensure they are functioning. Many types produce a ~20-kHz tone as a by-product of this monitoring.	~20 kHz	76 dB	Fletcher et al., 2018c
			65 dB	Paxton et al., 2018
			43-82 dB	Mapp, 2018
Incidental	Acoustic spotlights: Two high-intensity ultrasonic beams overlap, and the nonlinear difference frequency produces a low-power audible signal so that listeners to recordings who share a space do not bother one another (for museums, exhibitions, and homes). It is not known whether anecdotal reports of adverse effects, if confirmed, would be due to the fundamental, a subharmonic produced by the source of a nonlinearity in propagation, or when the ear is driven by the signals.	~20 kHz	53 dB at 3.5 m	Dolder et al., 2019 Sapozhnikov et al., 2019
		~40 kHz	118 dB at 3.5 m	
Incidental	Haptic feedback: ultrasonic beams (e.g., above a computer keyboard) produce modulated radiation pressure that gives the sensation resembling "soap bubbles bursting on the skin."	~40 kHz	125 dB at 60 cm	Battista, 2019
			155 dB at 20 cm	Lieber et al., 2019

SPL, sound pressure level, TOB, third-octave band; EU, European Union. See Leighton, 2016a, for details of devices. Reproduced from Leighton et al., 2020.

centered on 25-50 kHz (i.e., from the limits of 22.4 to 56.2 kHz) and 75 dB for the TOBs centered on 8-16 kHz (i.e., having limits from 7.07 to 17.8 kHz).

After assessing the underpinning evidence, Leighton (2016a) concluded that this agreement did not result from various bodies independently validating each other but instead from each copying predecessors rather than face the prospect of funding difficult experiments to determine the MPLs for themselves. However, even without the US Occupational Safety and Health Administration (OSHA), there was still about a 50 dB variation in MPL in the TOB centered on 20 kHz (Leighton, 2016a). Since 2004, the OSHA guideline was an outlier, permitting an extra 30 dB on MPLs for airborne ultrasound (Howard et al., 2005), a recommendation it recently dropped (Leighton, 2019).

Although occupational airborne ultrasound exposure from industrial equipment (e.g., welders, drills, cleaning baths) drove occupational MPLs for decades, public exposure was largely ignored despite the fact that it also occurred from technologies such as pest deterrents (van Wieringen and

Figure 2. *Maps showing the location of airborne very high frequency sonic (VHFS) and ultrasound sources identified by members of the public using smartphones in Europe (***A***) and London (***B***). For a source to be included, spectrogram images from recordings at the site had to be e-mailed to the Health Effects of Ultrasound in Air (HEFUA) research group and have a clear spectral peak that was not typical of usual background noise.* ***Red symbols****, sources that have peaks from 17.8 to 22.4 kHz (in the 20-kHz third-octave band [TOB]);* ***blue symbols****, sources that have peaks from 15 to 17.7 kHz. The limited sample rate of smartphones means that higher frequency sources could not be recorded. Reproduced from Fletcher et al., 2018c, with permission.*

Glorieux, 2018). The issue of public exposure is becoming more urgent as there have recently been additional devices (**Table 1**) used or proposed that generate both deliberate and incidental public exposures (Leighton, 2016a). Examples of source locations of airborne VHFS and ultrasound sources identified by members of the public using smartphones are shown in **Figure 2**. For a source to be included, spectrogram images from recordings at the site had to be e-mailed to the Health Effects of Ultrasound in Air (HEFUA) research group and have a clear spectral peak that was not typical of usual background noise. Notably, these devices tend to generate tonal emissions, making the use of TOBs to describe MPLs particularly susceptible to difficulties when sounds fall at TOB boundaries.

Devices

Table 1 lists example devices that produce *incidental* ultrasonic exposures (as a by-product of the intended function) and *deliberate* ultrasonic exposures (from a device whose function is to expose a human/animal to ultrasound). Data on levels produced by commercial devices are extremely limited because there are no regulations requiring manufacturers to publish the output of devices. Accurately measuring exposures from these devices is complicated by the narrow beam width and short wavelength at these frequencies, requiring a high-resolution mapping of the sound field (**Figure 3**) to ensure that locally high exposures are not missed (Leighton, 2016a).

It is often assumed that airborne sound that is too high frequency to hear cannot cause adverse effects, although this remains unproven (Leighton, 2017). To discuss device exposure, it is important to first know to what the outputs can be compared. **Table 2** has the MPLs in TOBs according to OSHA (2015) in the United States and ICNIRP (INIRC-IRPA, 1984). A MPL is the maximum value the SPL should reach measured with the "slow" time weighting on a sound level meter. The MPLs discussed here are Z-weighted (i.e., flat frequency weighting) and are considered at the location of exposure that may not be specifically at a 1-meter distance (Ueda et al., 2014a). Leighton (2016a) describes a range of other applications that could generate public exposures to airborne ultrasound, including wireless charging of phones via airborne ultrasound and ultrasonic beacons to communicate covertly from computers and TVs to an individual's smartphone without their knowledge to provide data on viewing habits.

The Response of the Human Ear to Ultrasound

Human HTL increases (i.e., hearing acuity reduces) as frequency increases above about 4 kHz, with the HTL

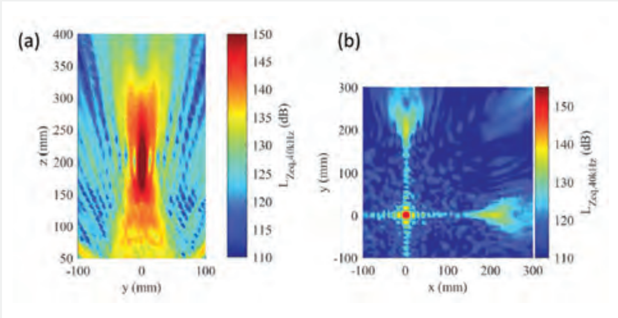


Figure 3. *The spatial distribution of* $\mathbf{L}_{Zeq,40kHz}$ *(the unweighted equivalent continuous sound pressure level in the TOB centered on 40 kHz) plotted in a vertical (**a**) and a horizontal (**b**) plane through the focus where the human is meant to interact with an ultrasonic field to produce haptic feedback (such that **b** is measured at z = 200 mm) at maximum setting. Figure was taken at the Physikalisch-Technische Bundesanstalt (PTB) using a ⅛-inch microphone (from Liebler et al., 2019). Reproduced from Leighton et al., 2019, with permission.*

increasing more sharply with a frequency above 10 kHz (Ashihara et al., 2006). Testing 18-33 year olds, Ashihara et al. (2006) found some individuals having HTLs around 90 dB SPL at 24 kHz, although this upper frequency was determined partly by limits on the SPL imposed by the equipment or safety regulations. Good hearing at ultrasonic frequencies can persist into older adulthood. Of those tested, Rodriguez Valiente et al. (2014) found that 5% of 40-49 year olds had better HTLs at 20 kHz than the median 20-29 year old. The increase in HTL with frequency in the VHFS range is due to (1) increasing middle ear attenuation and (2) the fact that the stimulus frequency begins to exceed the highest natural frequency of the basilar membrane (which is found at its base), leading to a reduction in the size of the receptive region of the cochlea (Yasin and Plack, 2005). Measured VHFS HTLs reflect the sensitivity to sound of the ear rather than of the mechanoreceptors in the skin, which are far less sensitive, particularly above about 1 kHz (Boothroyd and Cawkwell, 1970).

Subharmonics generated by source or propagation are discussed in **Table 1**. Ultrasonic stimuli at sufficiently high SPLs may also generate subharmonics in the middle ear vibration, leading to perception arising from other regions of the basilar membrane. However, studies employing masking stimuli suggest that at the SPLs considered in this article up to 24 kHz, it is the fundamental frequency component of ultrasound rather than the subharmonics that is perceived (Ashihara et al., 2006). Consequently, at least up to 24 kHz, excitation of this basal cochlear region is thought to be the most likely origin of the auditory sensations discussed here.

Aging, ototoxic drug exposure, and (possibly) noise exposure all appear to cause damage initially at the cochlear base, showing up as increases in HTLs first at very high frequencies, then later at lower audio frequency HTLs. HTLs in the ultrasonic range are generally lower in children than in adults (Rodriguez Valiente et al., 2014), and, consequently, adults in decision-making positions may be unaware of problems that only affect children and teenagers.

In addition, the variability in HTLs between individuals increases greatly with frequency. Thus, in the population of healthy young adults, the intersubject standard deviation

Table 2. *Maximum permissible levels according to different guidelines for TOBs between 20 and 40 kHz*

TOB	OSHA Occupational Level	ICNIRP Occupational Level	ICNIRP Public Exposure Level
20	105	75	70
25	110	110	100
31.5	115	110	100
40	115	110	100

ICNIRP, International Commission on Non-Ionizing Radiation Protection occupational levels can be increased for shorter exposures, whereas public exposures levels cannot. TOB is in kHz; levels are in dB re 20 μPa. Reproduced from Dolder et al. (2019).

of HTLs (in dB) at 18 kHz is around 3 times that at 1 kHz (Rodriguez Valiente et al., 2014). This variability appears to arise partly from the cochlea and middle ear but also from the sound field in the ear canal that becomes increasingly complex at high frequencies and depends critically on the dimensions and shape of the pinna, ear canal, and tympanic membrane (Leighton, 2016a).

Human Adverse Effects

The authors have their own anecdotes of people adversely affected by audible ultrasound (e.g., discomfort, headaches, failure to concentrate, and falling off chairs at the sudden onset of a tone). We also have reports from people who are convinced that they have been affected but are unlikely to have been (e.g., they report that the sound follows them from country to country). Laboratory studies of the symptoms listed above are further complicated by a reliance on subjective ratings which audio frequency studies indicate are affected by nonacoustic factors such as the context in which sounds are presented and the subject's mood and attitudes (Miedema and Vos, 1999). Despite these complications, laboratory tests are able to reveal differences between responses to ultrasound and responses to lower audio frequency exposure, thereby controlling for nonauditory effects. Such tests have consistently found that audible stimuli become more aversive as their frequency increases into the VHFS and ultrasonic ranges when controlling the stimulus level either for ratings of subjective loudness or for sensation level (where *sensation level* is defined as the level of the stimulus above the individual's HTL). Subjects rated VHFS emissions and ultrasound to be worse than lower audio frequency sounds on scales of unpleasantness, discomfort, annoyance, and distractedness (Fastl and Zwicker, 2007; Kurakata et al., 2013; Fletcher et al., 2018a). This is consistent with the case study described in **The Context of This Case Study**.

Moreover, the usable dynamic range (i.e., the difference in SPL between extreme unpleasantness and inaudibility) reduces as frequency increases, so subjects can find VHFS stimuli extremely unpleasant and annoying even when only at a sensation level of 10 or 20 dB above HTL (Kurakata et al., 2013; Leighton, 2017; Fletcher et al., 2018a; EARS II, 2019). There also appears to be a subpopulation of unknown size who find VHFS exposure particularly annoying despite not suffering from hyperacusis (a low tolerance of everyday loud sounds; Fletcher et al., 2018a; EARS II, 2019).

Why Are Higher Frequency Sounds Aversive?

Why higher frequency sounds are more aversive is unknown. Suggested reasons include their rarity, associations with human or animal vocalizations, or differences in physiology between higher and lower frequency receptive areas in the cochlea. Many commercial sources of airborne ultrasound are tonal. Applying either amplitude or frequency modulation to a pure tone at lower audio frequencies is found to increase perceived unpleasantness (Fastl and Zwicker, 2007; Kumar et al., 2008). However, in the VHFS and ultrasonic ranges, modulation is often perceived differently due to the limited dynamic range available (the difference between audible and tolerable SPLs) and the steep gradient of the HTL-frequency curve, which strongly couples any frequency modulation to modulations of audibility or subjective loudness. Hence, in our studies of unpleasantness and discomfort, we used unmodulated pure tones (with durations of at least 0.5 s; Fletcher et al., 2018a).

Symptoms Associated with Airborne Ultrasound

Other symptoms anecdotally attributed to audible airborne ultrasonic exposure are even more difficult to study because they appear only after some time following the stimulus onset (Leighton, 2016a). These include nausea, headache, dizziness, ear pain, fatigue, and anxiety. So far, controlled studies (at the limited exposures allowed) have not found that audible ultrasound can reliably provoke these specific symptoms. Those self-diagnosing as symptomatic from previous public exposures had difficulty concentrating and greater annoyance and, like the group who did not self-diagnose in this way, showed greater discomfort (Fletcher et al., 2018a). For our laboratory testing, we worked within an ethical framework that limited human exposures to an 8-hour equivalent continuous SPL of 76 dB per day. This equates to 85 dB per hour. Because this is far lower than some SPLs to which the public can be exposed day-to-day, our laboratory data of adverse human responses cannot explore the exposures to which some subjects attribute adverse effects.

The symptoms attributed to airborne ultrasound may arise from processes similar to those arising at lower audio frequencies. Epidemiological studies show that chronic environmental noise exposure at lower audio frequencies is a likely cause of several adverse effects in humans, including severe annoyance, sleep disturbance, cardiovascular disease, and impaired cognitive development in children (WHO, 2011; Murphy, 2017). One suggested physiological mechanism is an autonomic response to a perceived threat, leading to increased release of stress hormones and other stress-related responses (Murphy, 2017). It is plausible that exposure to an unacceptable sound could lead to anxiety and stress, particularly if the source is unidentified and its existence is disputed by other people (Leighton, 2018). However, to date, few epidemiological studies have been conducted on the prevalence of adverse effects in people exposed to ultrasound. The choice of population studied is important because we know the effect will be on a minority of the general population. Still, for public exposures, this might constitute millions of people, and so we do not wish the data from this minority to be lost through averaging (Leighton, 2016a, 2017; Leighton et al., 2019).

Some members of the public have anecdotally reported adverse symptoms that they attributed to ultrasound even though the sound was inaudible and identified only by seeing a sound source and detecting ultrasound using a smartphone. We therefore tested whether adverse effects could be provoked by inaudible ultrasound in a double-blind study (Fletcher et al., 2018b). Two groups of subjects were recruited: those who self-reported previously finding VHFS sounds aversive and those who did not. Each subject's HTL was measured at 20 kHz, and the SPL of the ultrasound was set at least 15 dB below this to ensure that the ultrasound remained inaudible and hence was not immediately distinguishable from a sham exposure condition (e.g., no ultrasound). SPLs ranged from 57 to 88 dB (the ethical upper limit) depending on the subject's HTL. Subjects then experienced both genuine and sham exposures, each being presented continuously for 20 minutes.

No adverse effects of ultrasound were found compared with sham exposure in either subject group. Neither were the subjects able to correctly distinguish genuine from sham ultrasound after a 20-minute period. This does not mean that adverse effects are impossible, but rather that they could not be provoked in this participant sample and at the amplitudes, frequencies, and durations that we were ethically permitted to use. A longer term single-blind study of inaudible ultrasound also found no evidence of symptoms of genuine compared with sham ultrasound exposure (EARS II, 2019). Both studies found some evidence of nocebo effects (an adverse response arising from the subject's erroneous belief that they are being exposed; Fletcher et al., 2018b; EARS II, 2019).

Claims of Attacks on United States Embassies

We have not had access to the raw data on the claims of ultrasonic attacks on embassies in Cuba and China. Consequently, we could only make an assessment based on the information published in the media and in peer-reviewed journals (Leighton, 2018; Swanson et al., 2018). We concluded that the evidence suggests that it is unlikely that ultrasound or VHFS exposure (whether perceptible or imperceptible) caused the ill effects that were reported in brain injury tests some 200 days later (Leighton, 2018).

It would be easy to hide a pest-scarer in a room that could disturb a minority of the population in that room only. However, the embassy staff reportedly targeted would likely be robust against such attacks because they were typically over 30 years old. Those susceptible would most likely be children, and it would therefore make an odd choice for targeting an embassy. It would be technically far more challenging to project ultrasound over long distances or through a substantial wall. The science underpinning the neurological damage reported by the mass media has been challenged (Della Sala and Cubelli, 2018; Leighton, 2018).

Conclusions: What Do We Think Is Really Going On?

At the levels of high-frequency sound to which the public are currently exposed, most people will be unaffected, although a minority will be too disturbed to complete tasks and (possibly) a small number will experience headaches, nausea, tinnitus, and other problems. The effects are likely to disappear if the exposure ceases. That is not to underplay the significance because these are avoidable exposures that can be unpleasant to a minority and detrimental to the quality of life if they persist. Although most people will feel no effect at those levels, if the site is a railway station or a mall, the minority who are affected may number thousands each day, some of whom might work there for several hours.

It is important to consider the mechanisms through which headaches and other symptoms might arise. The evidence remains inconclusive. However, we suggest two potential causes. The first is a stress response to audible VHFS or ultrasonic stimuli, which appear to be particularly intrusive (at least for some people).

The second is anxiety arising from the sufferer's emotional or cognitive response either to audible ultrasound or the (possibly mistaken) belief in its presence (e.g., fear that ultrasound may be causing injury, even if inaudible). Such anxiety might be enhanced if the sufferer knows that the exposure is involuntary, that others cannot hear it, that it will continue without their control at their place of work or home or in their child's classroom, and especially if they think that it is maliciously targeted at them. Indeed, we have received a surprisingly large number of inquiries claiming ultrasonic attacks by neighbors, and we always recommend testing for such signals with a smartphone.

This article has not covered the issue of human adverse effects to infrasound or audio frequency sonic deterrents (apart from a brief mention of teen deterrents; Leighton 2016a), such as LRAD devices (which currently do not emit their main signal above ~3 kHz but are sometimes inaccurately confused with parametric devices and thought of as high-power "spotlights" for crowd control; Leighton, 2016a). This article also does not cover electromagnetic emissions or ultrasound as applied into the body for fetal scanning. This distinction is mentioned here because these issues are frequently raised by some readers/listeners when we discuss the adverse effects of ultrasound in air on humans, and they are outside the scope.

Acknowledgments

Financial support from the Colt Foundation (Ref. No. CF/03/15) and the European Metrology Programme of Innovation and Research (EMPIR; Grant 15HLT03 EARII) is gratefully acknowledged. The EMPIR programme is cofinanced by the participating states and from the European Union Horizon 2020 research and innovation program.

References

Ashihara, K., Kurakata, K., Mizunami, T., and Matsushita, K. (2006). Hearing threshold for pure tones above 20 kHz. *Acoustical Science and Technology* 27, 12-19. https://doi.org/10.1250/ast.27.12.

Battista, A. (2019). The effect of 40 kHz ultrasonic noise exposure on human hearing. *Proceedings of the 23rd International Congress on Acoustics*, Aachen, Germany, September 9-13, 2019, pp. 4783-4788. Available at https://bit.ly/3gMHYxT. Accessed May 30, 2020.

Boothroyd, A., and Cawkwell, S. (1970). Vibrotactile thresholds in pure tone audiometry. *Acta Oto-Laryngologica* 69, 381-387.

Conein, E. (2006). *Compound Security Systems 'Mosquito' Sonic Deterrent Report on Acoustic Tests Performed 6th April 2006*. NHS Memorandum Ref. 06nstaffsp.com dated April 12, 2006, Gloucester Hospitals, Gloucester, UK. Available at https://bit.ly/2XqFfCv. Accessed May 30, 2020.

Della Sala, S., and Cubelli, R. (2018). Alleged "sonic attack" supported by poor neuropsychology. *Cortex* 103, 387-388.

Dolder, C. N., Fletcher, M. D., Lloyd Jones, S., Lineton, B., Dennison, S. R., Symmonds, M., White, P. R., and Leighton, T. G. (2018). Measurements of ultrasonic deterrents and an acoustically branded hairdryer: Ambiguities in guideline compliance. *The Journal of the Acoustical Society of America* 144, 2565-2574. https://doi.org/10.1121/1.5064279.

Dolder, C. N., Fletcher, M. D., Lloyd Jones, S., Lineton, B., and Leighton, T. G. (2019). Exposure levels for parametric arrays in light of guideline ambiguities. *Proceedings of the 23rd International Congress on Acoustics*, Aachen, Germany, September 9-13, 2019, pp. 6359-6362. Available at http://pub.dega-akustik.de/ICA2019/data/ICA19_manuscripts_all.pdf. Accessed January 1, 2020.

EARS II (2019). *Final Publishable Report: Metrology for modern hearing assessment and protecting public health from emerging noise sources*. Project No. 15HLT03, EURAMET, Braumschwieg, Germany. Available at https://bit.ly/3ch1leP. Accessed May 28, 2020.

Fastl, H., and Zwicker, E. (2007). *Psychoacoustics: Facts and Models*. Springer-Verlag, Berlin Heidelberg, Germany.

Fletcher, M. D., Jones, S. L., White, P. R., Dolder, C. N., Leighton, T. G., and Lineton, B. (2018a). Effects of very high-frequency sound and ultrasound on humans. Part I: Adverse symptoms after exposure to audible very-high frequency sound. *The Journal of the Acoustical Society of America* 144, 2511-2520. https://doi.org/10.1121/1.5063819.

Fletcher, M. D., Jones, S. L., White, P. R., Dolder, C. N., Leighton, T. G., and Lineton, B. (2018b). Effects of very high-frequency sound and ultrasound on humans. Part II: A double-blind randomized provocation study of inaudible 20-kHz ultrasound. *The Journal of the Acoustical Society of America* 144, 2521-2531. https://doi.org/10.1121/1.5063818.

Fletcher, M. D., Jones, S. L., White, P. R., Dolder, C. N., Lineton, B., and Leighton, T. G. (2018c). Public exposure to ultrasound and very high frequency sound in air. *The Journal of the Acoustical Society of America* 144, 2554-2564. https://doi.org/10.1121/1.5063817.

Howard, C. Q., Hansen, C. H., and Zander, A. C. (2005). A review of current ultrasound exposure limits. *Journal of Occupational Health and Safety, Australia and New Zealand* 21, 253-257.

INIRC-IRPA (International Non-Ionizing Radiation Committee of the International Radiation Protection Association). (1984). Interim guidelines on the limits of human exposure to airborne ultrasound. *Health Physics* 46, 969-974.

Kumar, S., Forster, H. M., Bailey, P., and Griffiths, T. D. (2008). Mapping unpleasantness of sounds to their auditory representation. *The Journal of the Acoustical Society of America* 124, 3810-3817. https://doi.org/10.1121/1.3006380.

Kurakata, K., Mizunami, T., and Matsushita, K. (2013). Sensory unpleasantness of high-frequency sounds. *Acoustical Science and Technology* 34, 26-33. https://doi.org/10.1250/ast.34.26.

Leighton, T. G. (2016a). Are some people suffering as a result of increasing mass exposure of the public to ultrasound in air? *Proceedings of the Royal Society A: Mathematical Physical and Engineering Sciences* 472, Article ID 20150624. https://doi.org/10.1098/rspa.2015.0624.

Leighton, T. G. (2016b). *How a Smartphone or Tablet Computer Can Monitor for Ultrasound in Air.* Available at https://bit.ly/2MmF3xR. Accessed May 10, 2020.

Leighton, T. G. (2017). Comment on 'Are some people suffering as a result of increasing mass exposure of the public to ultrasound in air?' *Proceedings of the Royal Society A: Mathematical Physical and Engineering Sciences* 473, Article ID 2060828. https://doi.org/10.1098/rspa.2016.0828.

Leighton, T. G. (2018). Ultrasound in air — Guidelines, applications, public exposures, and claims of attacks in Cuba and China. *The Journal of the Acoustical Society of America* 144, 2473-2489. https://doi.org/10.1121/1.5063351.

Leighton, T. G. (2019). Ultrasound in air: New applications need improved measurement methods and procedures, and appreciation of any adverse effects on humans. *Proceedings of the 23rd International Congress on Acoustics*, Aachen, Germany, September 9-13, 2019, pp. 6326-6332. Available at http://pub.dega-akustik.de/ICA2019/data/ICA19_manuscripts_all.pdf. Accessed January 1, 2020.

Leighton, T. G., Currie, H. A. L., Holgate, A., Dolder, C. N., Jones, S. L., White, P. R., and Kemp, P. S. (2019). Analogies in contextualizing human response to airborne ultrasound and fish response to acoustic noise and deterrents. *Proceedings of Meetings on Acoustics* 37, 010014. https://doi.org/10.1121/2.0001260.

Liebler, M., Kling, C., Best, B.,Gerlach, A., and Koch, C. (2019). Quantitative characterization of high-intensity focused airborne ultrasonic fields. *Proceedings of the 23rd International Congress on Acoustics*, Aachen, Germany, September 9-13, 2019, pp. 6338-6345. Available at http://pub.dega-akustik.de/ICA2019/data/ICA19_manuscripts_all.pdf. Accessed January 1, 2020.

Mapp, P. A. (2018). Potential audibility of ultrasonic signal monitoring of Public Address and Life Safety Sound Systems. *The Journal of the Acoustical Society of America* 144, 2539-2547. https://doi.org/10.1121/1.5063993.

Miedema, H. M. E., 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. https://doi.org/10.1121/1.424662.

Murphy, E. (2017). What to do about environmental noise? *Acoustics Today* 13(2), 18-25.

OSHA (Occupational Safety and Health Administration). (2015). *OSHA Technical Manual, Noise: Section III, Chapter 5-Ultrasound*. OSHA, US Department of Labor, Washington, DC.

Paxton, B., Harvie-Clark, J., and Albert, M. (2018) Measurements of ultrasound from public address and voice alarm systems in public places. *The Journal of the Acoustical Society of America* 144(4), 2548-2553. https://doi.org/10.1121/1.5063811.

Rodriguez Valiente, A., Trinidad, A., Garcia Berrocal, J. R., Gorriz, C., and Ramirez Camacho, R. (2014). Extended high-frequency (9-20 kHz) audiometry reference thresholds in 645 healthy subjects. *International Journal of Audiology* 53, 531-545. https://doi.org/10.3109/14992027.2014.893375.

Sapozhnikov, O. A., Khokhlova, V. A., Cleveland, R. O., Blanc-Benon, P., and Hamilton, M. F. (2019). Nonlinear acoustics today. *Acoustics Today*, 15(3), 55-64. https://doi.org/10.1121/AT.2019.15.3.55.

Swanson, R. L., Hampton, S., Green-McKenzie, J., Diaz-Arrastia, R., Grady, M. S., Verma, R., Biester, R., Duda, D., Wolf, R. L., and Smith, D. H. (2018). Neurological manifestations among US government personnel reporting directional audible and sensory phenomena in Havana, Cuba. *Journal of the American Medical Association* 319, 1125-1133.

Ueda, M., Ota, A., and Takahashi, H. (2014a). Investigation on high-frequency noise in public space. *Proceedings of the 43rd International Congress on Noise Control Engineering: Improving the World Through Noise Control* (INTERNOISE 2014), The Australian Acoustical Society, Melbourne, VIC, Australia, November 16-19, 2014, vol. 249, pp. 2692-2698.

Ueda, M., Ota, A., and Takahashi, H. (2014b). Investigation on high-frequency noise in public space. We tried noise abatement measures for displeasure people. *Proceedings of the 7th Forum Acusticum*, Krakow, Poland, September 7-12, 2014, paper PJ06_7, 5.

van Wieringen, A., and Glorieux, C. (2018). Assessment of short-term exposure to an ultrasonic rodent repellent device. *The Journal of the Acoustical Society of America* 144, 2501-2510. https://doi.org/10.1121/1.5063987.

WHO (World Health Organization). (2011). *Burden of Disease from Environmental Noise. Quantification of Healthy Life Years Lost in Europe*. WHO, Copenhagen, Denmark.

Yasin, I., and Plack, C. J. (2005). Psychophysical tuning curves at very high frequencies. *The Journal of the Acoustical Society of America* 118, 2498-2506. https://doi.org/10.1121/1.2035594.

About the Authors

Timothy G Leighton
T.G.Leighton@soton.ac.uk

Institute of Sound and Vibration Research (ISVR)
University of Southampton
Highfield, Southampton SO17 1BJ, UK

Timothy G. Leighton, FRS FREng FMedSci ScD, is the founder and chair of the Global Network for AntiMicrobial Resistance and Infection Prevention (Global-NAMRIP). He is professor of ultrasonics and underwater acoustics at the Institute of Sound and Vibration Research, University of Southampton, UK, and a director and inventor-in-chief of Sloan Water Technology Ltd., a UK manufacturer and R&D establishment founded on his patents. He is a Fellow of the Acoustical Society of America. He founded and leads the Health Effects of Ultrasound in Air (HEFUA), which has members across the United Kingdom interested in the topic.

Ben Lineton
B.Lineton@soton.ac.uk

Institute of Sound and Vibration Research (ISVR)
University of Southampton
Highfield, Southampton SO17 1BJ, UK

Ben Lineton is a lecturer in hearing science at the University of Southampton, UK. His research covers a wide range of areas including modeling cochlear mechanics and otoacoustic emissions and hearing in the high-frequency range.

Continued on page 26

Craig Dolder
C.N.Dolder@soton.ac.uk
Institute of Sound and Vibration Research (ISVR)
University of Southampton
Highfield, Southampton SO17 1BJ, UK

Craig Dolder obtained his BSE in acoustical engineering at the University of Hartford, CT. He obtained his PhD in May 2014 from The University of Texas at Austin where he worked for the Applied Research Laboratories researching various topics including fish school acoustics and turbulent flow noise. In August 2015, he moved to the University of Southampton, UK, for postgraduate work on ultrasonics and bioreactors and joined Sloan Water Technology Ltd. as the senior research scientist in 2019. He enjoys participating in public engagement events, teaching about all aspects of acoustics.

Mark Fletcher
M.D.Fletcher@soton.ac.uk
University of Southampton Auditory Implant Service
Highfield, Southampton SO17 1BJ, UK

Mark Fletcher is a senior research fellow at the University of Southampton Auditory Implant Service, UK, and leads the Electro-Haptics and Virtual Acoustics for Clinic research projects. Mark also cocreated the RealSpeech auditory training app, which focuses on the recreation of highly realistic auditory environments and is currently part of a UK-wide trial as part of the CHOICE remote care platform. Mark did his PhD at the Institute of Hearing Research, where he used auditory psychophysics and otoacoustic emissions to help develop methods for measuring top-down control of cochlear processing in humans.