Public exposure to ultrasound and very high-frequency sound in air

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Recent work showing the presence of a new generation of ultrasound (US) sources in public places has reopened the debate about whether there are adverse effects of US on humans, and has identified weaknesses in standards and exposure guidelines. Systems that rely on very high-frequency sound (VHFS) and US include public-address voice-alarm (PAVA) systems (whose operational status is often monitored using tones at ∼20 kHz) and pest deterrents. In this study, sound pressure levels (SPLs) produced by 16 sources that were either publically available or installed in busy public spaces were measured. These sources were identified through a citizen science project, wherein members of the public were asked to provide smartphone recordings of VHFS/US sources. With measurements made in realistic listening positions, pest deterrents were found that produced levels of up to 100 dB SPL at ∼20 kHz, and a hand dryer was found to produce 84 dB SPL at 40 kHz. PAVA systems were found to emit lower levels of up to 76 dB SPL at ∼20 kHz. Pest deterrents measured breach recommended safe listening limits for public exposure for people who are nearby even for relatively short periods. *© 2018 Acoustical Society of America.*

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I. INTRODUCTION

Recent detection of tonal ultrasound (US; > 17.8 kHz) in public places has reopened the question of whether there are adverse effects of US on humans, and identified weaknesses in measurement techniques, standards, and safe exposure guidelines (Leighton, 2016b, 2017). These tonal public exposures differ markedly from the occupational, often broadband, exposures that characterized interest in this field in the past. Since the late 1940s, when the development of jet engines and powerful sirens meant that people were, for the first time, being exposed to high-intensity US, there have been reports of adverse effects of US in air on humans (see Pharris, 1948; Graff, 1981; Lawton, 2001). This has given rise to a number of studies (typically on factory workers), which have documented a range of effects of very high-frequency sound (VHFS; 11.2–17.8 kHz) and US, including nausea, tinnitus, fatigue, headache, dizziness, and pressure or pain in the ears (e.g., Skillern, 1965; Acton and Carson, 1967; Acton, 1974; Crabtree and Forshaw, 1977; Herman and Powell, 1981; Acton, 1983; Maccà *et al.*, 2014; Ueda *et al.*, 2014; Fletcher *et al.*, 2018a,b). However, the evidence base for these and more recent reports of similar symptoms by members of the public of effects of VHFS/US remains limited, with studies commonly being confounded by the presence of intense energy below the very high-frequency and ultrasonic ranges, the absence of a suitable control group, and the non-blinding of participants and researchers to whether US was present (Leighton, 2016b, 2017).

In recent years there has been an increase in the number of systems that employ VHFS/US signals in public spaces. This is in contrast to historical exposures, which tended to be primarily associated with specific workplace environments. The recently developed systems that rely on VHFS/US include public-address voice-alarm (PAVA) systems (whose operational status is often monitored using a system that generates tones at ∼20 kHz; see Mapp, 2016, 2017), pest repellents, and youth deterrents (such as the "Mosquito" device). There are also products that may, in the future, be available to members of the public who might expose themselves or others (e.g., domestic acoustic spotlights and phone technology; Leighton, 2007, 2016b, 2017). This paper aims to provide evidence about the current level of public exposure to these sounds by reporting a series of measurements made in public spaces at various sites in the United Kingdom (UK).

This work complements and expands on similar studies, which have made measurements of VHFS and US sources in public places. Ueda *et al.* (2014), for example, measured a rodent repellent *in situ* outside of a Tokyo restaurant with a level of up to around 130 dB sound pressure level [SPL (all SPLs stated re 20 μPa)] at ∼19 kHz. Measurements were made at a distance of 1.6 m, directly under the source (the angle of the measurement relative to the source was not stated). They also collected subjective reports of similar symptoms to those that have previously been reported, such

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as pain in the ears, irritation, restlessness, and heaviness in the head, when participants were exposed to the device *in situ*. Glorieux (2014) and van Wieringen (2014) also measured the sound level produced by an animal repellent, but under laboratory conditions. They measured levels of 76 dB SPL between 24 and 29 kHz at a distance of 6.5 m in front of the source (the height of the microphone relative to the source was not reported). Finally, most recently, Mapp (2016, 2017) presented measurements from a number of PAVA systems. Of the 50 surveyed, the majority produced sound levels below 55 dB SPL at 20 kHz, with only one system producing 79–82 dB SPL and four producing 75–78 dB SPL at 20 kHz (the distance and angle at which these measurements were taken from each source is not reported). In line with these findings, Leighton (2016b) measured PAVA sources in a museum and at a public swimming pool, which produced sound levels of 63 and 77 dB SPL at 20 kHz, respectively, at a distance of ∼1 m (an exceptionally loud source in a railway station, emitting 94 dB SPL at 19.4 kHz, was measured to emit a reduced level of 75 dB SPL on a return visit, following feedback to the operator).

Previous work has demonstrated the presence of devices in public spaces that produce VHFS and US at a wide range of SPLs. In this study, as part of a citizen science project, a number of sources were identified by members of the public using their smartphones, following the method outlined in Leighton (2016a,b). As could best be assessed from these records, locations of sources that appeared to output high sound levels and expose significant numbers of the public were shortlisted for follow-up investigation. Calibrated sound field measurements, which were traceable back to a primary standard (see Sec. II), were made of a subset of these sources *in situ* at realistic listening positions. The SPLs were mapped at various locations where access allowed us to assess spatial variability. In Sec. II, the process used to select measurement sites and methods used to make measurements are described. In Sec. III the results from this study are presented, and in Sec. IV the results are discussed and the conclusions summarized.

II. METHODS

At the outset of this study, we collected 30 reports from members of the public in the UK detailing symptoms experienced in the presence of VHFS and US sources. People were informed about the project using social media (Fletcher, 2016), newspaper articles (e.g., Gallagher, 2016), and appearances on news programs and podcasts (e.g., Mills, 2016). As part of this process, members of the public were asked to submit smartphone recordings of loud or troublesome sources, along with their location and a description or photograph of the suspected source. All public recordings reported were made between April 2016 and April 2017. Using these data, a shortlist of sources that had been identified as being likely to be loud or troublesome was drawn up. In preparation for a formal measurement with calibrated equipment, a preliminary visit was made to each site by the first author and levels were roughly estimated (±∼5 dB) for the energy contained up to 22 kHz, using a smartphone that had been cross calibrated against the microphone that would later be used for formal measurements (see below). This allowed confirmation of the presence of the source and allowed sources that were likely to be producing the highest levels of VHFS and US to be identified. These data were not used in the final sound level estimates. From this dataset, a final list of sound sources to be formally measured was made.

Within each location, measurements were taken from positions that were publicly accessible. Where possible, recordings were made from multiple positions around the source so that the maximum SPL could be assessed and information about how the SPL varies as a function of distance and azimuth could be obtained.

Written informed consent from the site owner or manager was obtained for all private locations where recordings were made. A guarantee of anonymity was given for all sites used in this study, and a short report detailing the findings was sent to each site owner or manager. All procedures were approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (application references: 26450 and 23717).

A. Recording and analysis

There are several difficulties when measuring VHFS/US sources in the field. Among these is the need to calibrate equipment for frequencies at and above 20 kHz, which few laboratories are able to do, and the requirement that the microphone be small, in order to reduce effects from small movements in microphone position (discussed in Mapp, 2017). Furthermore, sound level meters are usually not capable of measuring accurate SPLs above 20 kHz.

In this study, we used a bespoke measurement system to get around many of the issues associated with measuring VHFS/US sources. All calibrated measurements reported were made using a Bruel and Kjaer (B&K, Nærum, Denmark) free-field 1/2-in. 4191 microphone, with a B&K 2669 preamplifier, and B&K nexus 2690 conditioning amplifier (the amplifier's high and low pass cutoffs were set to 20 Hz and 100 kHz, respectively). The microphone and preamplifier were calibrated from 20 Hz to 50 kHz by the National Physical Laboratory (NPL) shortly before measurements began (measurements were taken between 5 April and 21 May 2017). The calibration was traceable back to primary standards for VHFS/US at the NPL, and the Danish Fundamental Metrology (DFM), with the calibration of the microphones checked by NPL against a reference microphone (International Electrotechnical Commission type WS3), which had been calibrated up to 200 kHz at DFM using a primary free-field calibration method. In the field, calibration checks were made before and after each measurement using a B&K 4231 sound calibrator. All recordings were made to disk using a Tascam DR40 recorder with a sample rate of 96 kHz and bit depth of 24 bits. For all recordings, the free-field microphone was hand held and pointed toward the center of the source (or the apparent center of the source where this was not clear), and the distance to the source was measured using either a laser distance measurer (Bosch GLR225, Gerlingen, Germany) or standard tape measure. At some sites, where there was a risk of the sound level estimate being influenced by wind or other airflow, a microphone windscreen was used (B&K UA-0237) and, in these cases, a correction was applied following the manufacturer's specification.

The data were analyzed using a custom MATLAB (Mathworks, Natick, MA) script to find the SPL (re 20 μPa) in 1/3-octave bands between 11.2 and 40 kHz (centered at 12.5, 16, 20, 25, 31.5, and 40 kHz), the precise frequency at which the SPL was greatest, and the overall SPL (across the whole frequency range from 20 Hz to 40 kHz). One-third-octave band (TOB) levels are reported for ease of comparison with existing guidelines (with raw data achieved for use of future researchers who may opt for different windowing criteria). In this study "ultrasonic" will refer to sound within or above the TOB centered on 20 kHz, that includes any frequency above 17.8 kHz, and not, as is more common, to sounds above 20 kHz (the notional upper limit of human hearing). This is because prior guidelines for the maximum permissible levels (MPLs), even when they have specifically defined US as referring to frequencies above 20 kHz, in fact, set the same MPL for tonal signals at 17.8 kHz –20 kHz as they did for signals at 20 kHz (Leighton, 2016b). VHFS will refer to sounds between 11.2 and 17.8 kHz (the upper limit of the 10-kHz TOB and the lower limit of the 20-kHz TOB). No additional frequency weighting was applied to the measured signal, which is equivalent to a Z-weighting for frequencies up to and including the 20-kHz TOB. Equivalent SPLs were estimated from 10 s segments of each recording (which was a multiple of the duty cycle of all sources measured that were not continuous). Segment start and end points were selected either at random, to cover a time point when background noise was at a minimum, or to capture a complete cycle of modulating sources.

An assessment was made of the amount of variability in the measurements that might be due to factors such as sensitivity of the recordings to small changes in microphone position and orientation (which can become more of an issue at very high frequencies owing to the shortness of the sound wavelength relative to the microphone size; Leighton, 2016b; Mapp, 2016, 2017) and changes in the acoustics in dynamically evolving environments. First, the root-mean-square (RMS) error was assessed between the original segment analyzed and two additional, randomly selected, non-overlapping segments for each recording location at three of the sites. In addition to this, at five sites, one measurement position was relocated and remeasured at the end of the recording session.

B. Sources

For all measurements, the acoustic source was estimated or identified based on a visual inspection of the device. Measurements were made with the microphone pointing toward the presumed source. For each source, a measurement was taken as close to the device as possible, an additional measurement was made on-axis to the presumed acoustic source when possible. All measurements were taken from a position that could easily be occupied by a member of the public. A range of VHFS/US source types was measured at a variety of recording locations. Sections II B 1–II B 3 detail the specifics for each source type in turn.

1. PAVA systems

Following requirements from British and other international standards (British Standards Institution, 2011, 2013, 2017), many PAVA systems in public places (which are also fire alarm and life safety systems) have their operational status monitored using a system that generates a tone at around 20 kHz. In this study, seven such systems were measured in a range of public locations. Systems that produced a constant tone rather than a pulsed tone were selected to be measured because the findings by Mapp (2017), together with the informal calibrated smartphone measurements in the current study, suggest that the equivalent level is likely to be significantly higher (by around 15 dB) and constant tone sources are more common (and therefore more likely to be encountered by members of the public). No windscreen was used for these recordings as they were all indoors. Five of the sites at which PAVA systems were recorded were train stations, and each of these sites had a footfall of tens of millions per year (ORR, 2016).

At each site the location of the PAVA system was determined and the closest publicly accessible position identified. Measurements were conducted starting at these proximate locations at a height of 1.75 m, and additional measurements were made in the vicinity, at different distances and azimuths. Distances reported are the direct distance from the microphone to the presumed acoustic source. The following sources and sites were measured.

a. PAVA 1. A single loudspeaker was built into a pillar, projecting out into a restaurant in a large, open railway station concourse. The bottom of the loudspeaker was 2.33 m from the floor and the loudspeaker was perpendicular to the floor. Measurements were made directly under the source, at 1, 2, and 4 m in front of the loudspeaker (in the plane perpendicular to both the speaker and the floor), and also at 1 and 2 m both at 45° and 90° relative to the aforementioned plane.

b. PAVA 2. A single loudspeaker was embedded in the ceiling in a corridor of a museum, pointing directly at the floor. The corridor was 2.1 m wide, 3 m high, and more than 10 m long. Measurements were made directly under the source (1.5 m away), down the corridor (3 m away), and at the edge of the corridor (1.65 m from the source).

c. PAVA 3. A single loudspeaker was mounted on a brick wall in a corner near the entrance to a major railway station. The base of the loudspeaker was 2.59 m from the floor. The loudspeaker was not quite perpendicular to the floor, being tilted slightly toward the floor. There was a short (∼1.25 m high) glass wall 2 m in front of the loudspeaker, and 2 m to the right of the loudspeaker there was another brick wall boundary with a large open entrance. Otherwise, the space was large and open. Measurements were made directly under the source, and at 1 and 2 m in front of the loudspeaker and at 1 and 2 m both at 45° and 90° azimuth relative to the front.

d. PAVA 4. A single loudspeaker was inset into a column in a large open railway station concourse. The base of the loudspeaker was 2.59 m from the floor and the loudspeaker was perpendicular to the floor. Measurements were made directly under the source, and at 1, 2, and 4 m in front of the source and at 2 m at 45° azimuth relative to the front.

e. PAVA 5. A single loudspeaker was attached to a column in a large open platform area in a railway station. The base of the loudspeaker was 3.12 m above the floor. The loudspeaker was not quite perpendicular to the floor, being tilted slightly toward the floor. Measurements were made directly under the source, at 1 and 2 m in front of the source, and at 1 and 2 m at 90° azimuth relative to the front.

f. PAVA 6. A single loudspeaker was attached to a wall just below the ceiling (4.25 m from the floor), above a large set of doors in a museum at approximately a 45° angle relative to the floor. The space opened out into a large hall and there were thick stone columns to the left and right of the loudspeaker (separated by 4 m), leaving a small walkway perpendicular to the loudspeaker. Measurements were made directly under the source, at 3.75 and 7.5 m in front of the source, and at 3.75 m at 90° azimuth relative to the front.

g. PAVA 7. A cluster of four loudspeakers was 8.13 m above a large open concourse area at a railway station. The loudspeakers were not quite perpendicular to the floor, all being tilted slightly toward the floor. Measurements were made directly under the source, 9 m from the source in front of one of the loudspeakers in the cluster, and also at distances of 7.5 and 15 m from the source, pointing toward the center of the cluster. An additional measurement was also made at 13.8 m directly in line with the center of the cluster (from an upper concourse area).

2. Pest deterrents

a. Pest deterrent 1. A cat deterrent in the garden of a private residence was 0.26 m from the ground and 0.4 m behind a short brick wall. Measurements were taken on axis 0.4 m from the source (crouched down 26 cm from the ground), at standing height 1.8 m (still 0.4 m horizontal distance) from the source (on a garden path), and on a public footpath 0.3 m behind the source. The microphone windscreen was on because the source was outdoors and unsheltered.

b. Pest deterrent 2. A cat deterrent was located at standing height in the garden of a private residence. Measurements were made from a garden path 0.3 m away from the source at standing height, both on axis and at 90° off axis, with the microphone windscreen on.

c. Pest deterrent 3. A bird deterrent was located near the main entrance to a school, projecting out to a large open courtyard. The source was attached to the school building 2.8 m from the ground and 9.1 m from the building entrance. A pathway passed perpendicular to the device and led onto a courtyard that reached out to the main gates. Beyond the gates was a pavement and road. Measurements were made from what would be expected to be common listening positions within the school grounds at 7.25 m, 9.6 m, and 14.5 m (at a slight angle relative to the front of the device, standing on the path and courtyard), 8.75 m (45° azimuth relative to the front, on the path), and 9.1 m 90° azimuth relative to the front (at the main entrance to the school building). A measurement was also made on the pavement (20.8 m from source) to assess the exposure level for passing members of the public. No windscreen was used as the location was sheltered from any wind, and on the day of recording wind was minimal.

d. Pest deterrents 4 and 5. The "Anti Mosquito–Sonic Repeller" smartphone app by Pico Brothers Ltd (http://www.picobrothers.com/; retrieved from the Apple app store, May 2017; pest deterrent 4), and "Anti Mosquito Repeller Ultrasonic" smartphone app by Andrew Neal (retrieved from the Apple store, May 2017; pest deterrent 5), both played on an Apple iPhone 6 smartphone. The measurements were made in a $4.75 \times 5.90\ \mathrm{m}^2$ courtyard (with no roof) with the phone on a 0.91 m high wooden table at the center of the courtyard. Measurements were made at 0.25 and 0.5 m from the source. No windscreen was used as the location was well sheltered from any wind.

3. Other sources

The final selection of products measured are a miscellany of devices that emit VHFS/US.

a. Hand dryers 1 and 2. In recent years, one innovative solution to the problem of perceived noise from some devices is to design a product so that the acoustic energy it emits lies in a high-frequency band where human hearing is less sensitive. This means that, whilst the overall acoustic output of the system may or may not be reduced, the perceived noise level is. Successful examples of the application of such technologies include hand dryers. Two forms of hand dryers were measured. The first, hand dryer 1, was a Dyson Airblade dB AB14 (Malmesbury, UK), which is of the innovative high-frequency design, whilst the second, hand dryer 2, an Airstream 5000 (Warner Howard World Dryers, Belfast, UK), is of more traditional design. Both devices were installed in different bathroom facilities, so the acoustic environments were not the same. Measurements were made in front of the source (facing the wall on which the device was mounted) at 0.4 m, 1 m, and 2 m. This was not directly in the airflow as neither the Dyson Airblade nor the AirStream devices project their airstreams outward to the front of the device. All measurements were made with the microphone windscreen on because of the increased airflow within the room caused by the devices. The conventional design hand dryer noise spectrum emitted its peak energy in the audio frequency band. In the high-frequency region acoustic energy decayed with frequency and

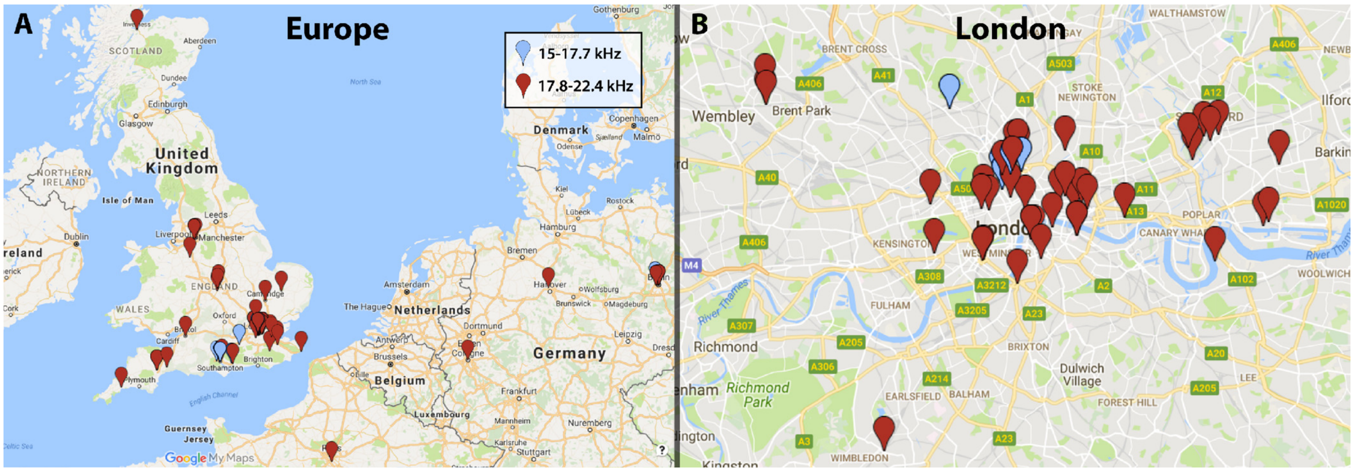

FIG. 1. (Color online) Maps showing the location of sources identified by members of the public using smartphones in (A) Europe and (B) London (Google Maps, 2017). For a source to be included on this map, spectrogram images from recordings at the site had to be emailed to the HEFUA (health effects of ultrasound in air) research group and have a clear peak in their spectrum that was not typical of usual background noise (e.g., from speech or a busy road). Sources in red (darker colored) have peaks at 17.8–22.4 kHz (in the 20-kHz 1/3 octave band) and those in blue (lighter colored) have peaks at 15–17.7 kHz. The limited sample rate of smartphones means that higher frequency sources could not be recorded.

there were no distinct peaks. Thus, this device was not regarded as a high-frequency acoustic source, it is not reported as such, and is used only for comparison purposes.

b. Door sensor. A GEZE door sensor (Lichfield, UK) was in a $3.1 \times 4.8 \times 2.54$ m^3 entrance hall. The source was 2.6 m from the floor. Measurements were made directly under the source at a distance of 0.85 m, and at 1 and 2 m. No microphone windscreen was used as the recording was made indoors.

c. CRT TV. A cathode ray tube television (CRT TV, which was part of a closed-circuit television system) was attached to a wall 1.71 m from the floor in a $6.22 \times 10.4 \times 2.84$ m^3 waiting room area. Measurements were made behind, to the side, and underneath the device at a distance of 0.1 m and to the side at distances of 1 and 2 m. No microphone windscreen was used as the recording was made indoors.

d. Dog whistle. A MaxiPaws Ultrasonic Dog Whistle (Southampton, UK) was measured in an open parkland area. Measurements were made at 0.25 and 0.5 m directly in front of the source. Measurements were made with the microphone windscreen on as this was an open outdoor environment with the possibility of wind.

III. RESULTS

A. Citizen science survey

In total, spectrograms for 88 sources with associated locations were submitted to us by members of the public (shown in Fig. 1). Of these, 76 were within the 20-kHz TOB and the remainder were between 15 kHz and the lower limit of the 20-kHz TOB (17.8 kHz). Of the 88 sources, 78 were in the UK. Of the sources identified, 47 (over 50%) were in London. PAVA systems appear to make up around 70% of submissions (based on device location and descriptions of sources from contributors). Around one-third of these PAVA system sources produced pulsed tones and the remainder produced constant tones. When the source pulsed, the pulse duration was most often around 1.5 s (minimum around 1 s, maximum around 10 s). The delay between pulses varied markedly between 1 and 40 s. These measurements were used only to identify the locations of sources for further measurements.

B. Calibrated measurements

Table I shows the maximum levels for each source measured and the distance from the source at which these levels were measured. Across all devices, the highest TOB levels measured were for pest deterrents 1 and 2, which were in the gardens of a private residence and produced maximum levels of 99.5 and 98.5 dB SPL (20-kHz TOB). These levels were taken directly in front of and close to the devices (0.3 m). When recording in a standing position (above the source), where one expects most exposures will occur, the level of pest deterrent 1 dropped to 75.8 dB SPL (20-kHz TOB) and was at a similar level of 74 dB SPL (20 kHz-TOB) at a position on the public footpath 1.4 m from the source), where passers-by might be exposed. The maximum level measured for pest deterrent 2 was at standing height (in-line with the deterrent). Pest deterrent 3, which was in operation at a school, was found to produce a maximum level of 66 dB SPL (12.5-kHz TOB) from a path within the school grounds. The level had fallen to 50.2 dB SPL (12.5-kHz TOB) on the pavement outside of the school gates. This measurement was made for comparison of public exposure and exposure within the school grounds (the measurement was not made at a precise doubling of distance relative to other measurement points so is not included in Fig. 4).

The PAVA systems produced levels between 60 and 75 dB SPL when measured at ranges of around 1 to 2 m. The systems measured in railway stations (PAVA 1, 3, 4, 5, and 7) all operated at the same frequency of 20.8 kHz. The levels observed in the museums (PAVA 2 and 6) were similar to those observed in railway stations. These levels are

TABLE I. Measurements of maximum SPLs above 11.2 kHz and overall SPLs. The overall level is computed across the spectrum 20 Hz–48 kHz. Most measured signatures from the sources had spectra that contained a consistent peak above the noise floor at the stated peak frequency. The only exception was the hand dryer whose spectrum was largely broadband and the quoted values are the highest peaks in the spectrum. Continuous tones were not frequency modulated unless their signal character was listed as "FM." Note that test-retest error may be substantial for some devices (see the end of Sec. III B).

Source	Distance from source (m)	Peak frequency (kHz)	Third octave band level [dB SPL; center frequency (kHz)]	Overall level (dB SPL)	Signal character	Measurement location
PAVA 1	2.4	20.8	75.4 (20)	76.7	Tonal, continuous	Station
PAVA 2	2.0	20	74.0 (20)	76.0	Tonal, continuous	Museum
PAVA 3	1.7	20.8	69.0 (20)	85.0	Tonal, continuous	Station
PAVA 4	1.0	20.8	69.0 (20)	74.0	Tonal, continuous	Station
PAVA 5	13.8	20.8	64.3 (20)	78.1	Tonal, continuous	Station
PAVA 6	1.7	20	62.4 (20)	70.7	Tonal, continuous	Museum
PAVA 7	2.5	20.8	61.0 (20)	75.9	Tonal, continuous	Station
Pest deterrent 1	0.4	19.6	99.5 (20)	99.6	FM	Garden
Pest deterrent 2	0.3	20.4	98.5 (20)	98.8	FM	Garden
Pest deterrent 3	9.6	12.5	64.2 (12.5)	73.8	FM	School
Pest deterrent 4	0.25	19.5	56.1 (20)	84.1	FM	Courtyard
Pest deterrent 5	0.25	15	53.5 (16)	77.1	Tonal, continuous	Courtyard
Hand dryer	0.4	39	84.0 (40)	99.2	Broadband	Bathroom
Door sensor	0.85	19.5	42.4 (20)	66.9	Tonal, continuous	Hallway
CRT TV	0.1	15.6	65.9 (16)	80.8	Tonal, continuous	Waiting room
Dog whistle	0.25	13.9	69.2 (12.5)	86.6	Tonal, continuous	Field

somewhat higher than the majority of sources measured by Mapp (2016, 2017), but are lower than the highest SPL that Mapp reported, which was in excess of 79 dB SPL.

Figure 2 presents spectrograms for some of the sources, which show the time-frequency structure of the signals being measured. Figure 3 illustrates the third octave spectra for four of the datasets. All PAVA systems measured showed a distinct, constant tone in the 20-kHz TOB, which was far above the acoustic noise floor for each site [see Figs. 2(A) and 3(A)]. In contrast, hand dryer 1 had significant energy across the whole frequency spectrum [Fig. 3(D)]. Figure 3(D) shows comparisons between the two hand dryers. The innovative dryer (hand dryer 1) produced significantly more energy in the very high-frequency and ultrasonic range than the comparison devices. For example, in the 12.5-kHz TOB, hand dryer 2 was 16.8 dB lower in level than hand dryer 1 and the difference increased with frequency up to the 40-kHz TOB, where the comparison device was 37.9 dB lower. Figure 3(C) shows examples of other VHFS sources, including the CRT TV, which produced 65.9 dB SPL in the 16-kHz TOB band, and the dog whistle, which produced 69.2 dB SPL in the 12.5-kHz TOB.

Figures 4 and 5 present data on the uniformity of exposure around the different sources at different recording locations. Figure 4 shows the change in sound level with increasing distance from the source (with a negative value representing a decrease in level), and Fig. 5 shows the level change with azimuth with the 0° position being in front of the loudspeaker (based on visual inspection). It should be noted that for many of the measurements, the sources were above the recording position and so a change in distance also meant a change in angle relative to the source. The data

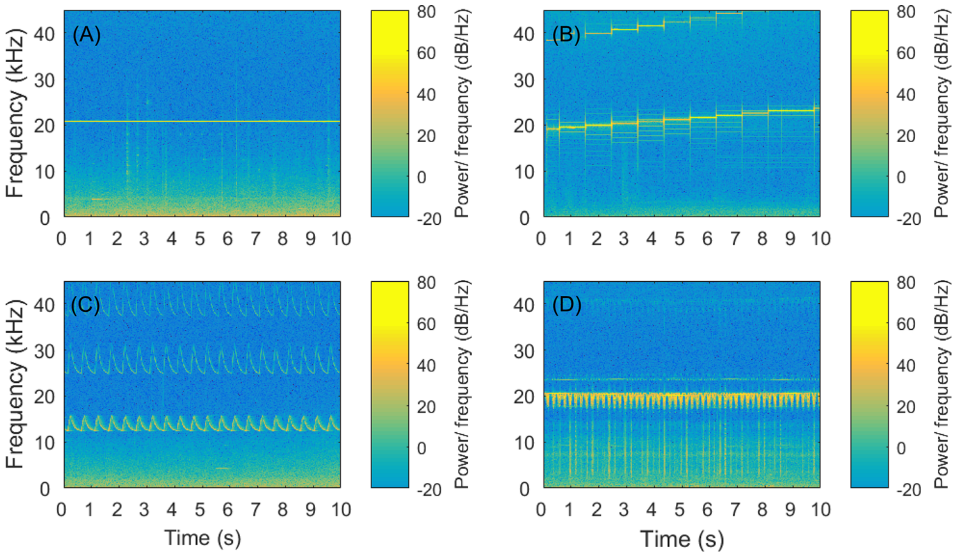

FIG. 2. (Color online) Spectrograms for four different source types measured. (A) shows PAVA 1 (a tonal continuous source), and (B), (C), and (D) show pest deterrents 1, 3, and 4, respectively (different types of frequency modulating source). Spectrograms used Hanning windowing with a window and bin width of 23.4 Hz (4096 point fast Fourier transform, FFT).

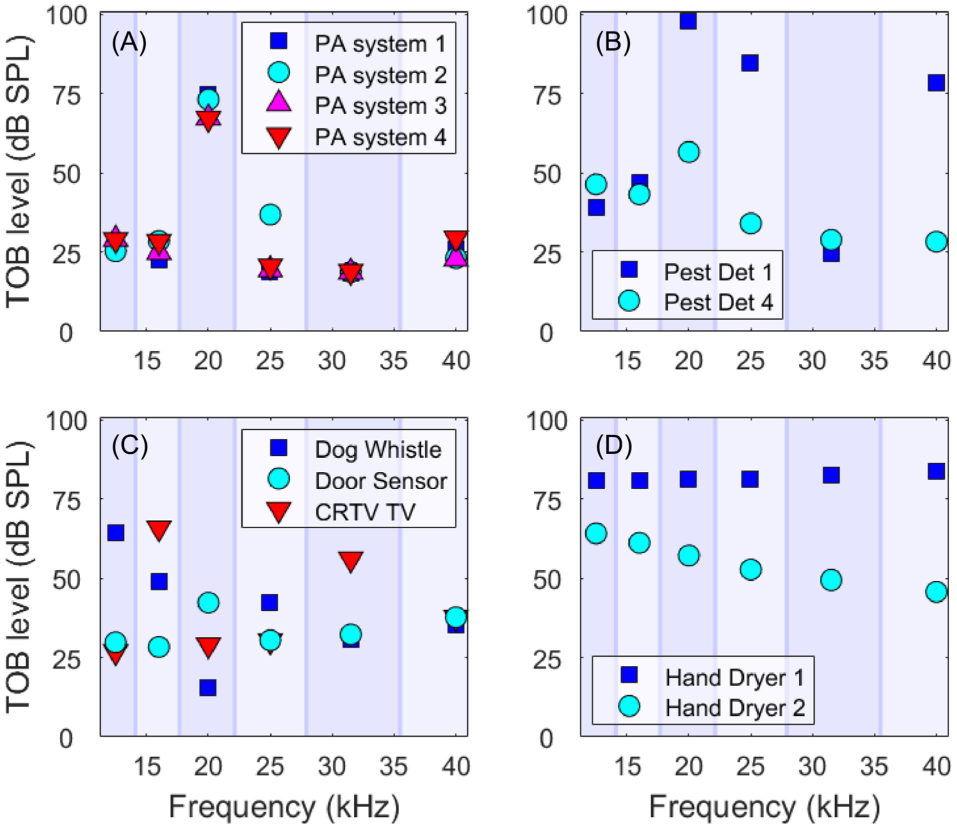

FIG. 3. (Color online) SPLs within 1/3-octave bands from 11.2–40 kHz for four different source types. One-third-octave band limits are marked in light blue in the background of each panel. A comparison device (see Sec. II, Methods) is shown for hand dryer 1 (D); note that the hand dryers were measured in different locations). Note that test-retest error may be substantial for some devices (see end of Sec. III B).

show a large variation across locations and devices in the change in SPL with doubling of distance (from +8 dB to −12.4 dB) and with measurement angle relative to the source (from +1.3 dB to −20.3 dB when moving from the front to 90° azimuth relative to the front). A reduction in sound level of 6 dB would be expected for each doubling of distance for a point source in an anechoic space (Fig. 4, grey line), plus a decay of less than 0.2 dB per meter (for a source at 20 kHz) due to atmospheric absorption (ISO 9613-1, 1993). As may be expected, the sound field generated by the PAVA systems, which were typically in large reverberant spaces, were more uniform (changed least with distance) on average than other sources [−1.9 ± 1.9 dB (standard error of the mean) with doubling of distance in front of the loudspeaker for the PAVA systems and −4.8 ± 1.4 dB for other devices], although variability across sites was large.

Repeatability measurements across a single continuous recording (comparing three non-overlapping samples) were made at all measurement locations for three sites (PAVA 6, PAVA 7, and pest deterrent 5). The RMS error across all locations for PAVA 6 was 0.8 dB, for PAVA 7 was 0.9 dB, and for pest deterrent 5 was 0.1 dB. Five retest measurements were also taken at different sites (PAVA 1, 3, and 4, and pest deterrents 4 and 5), where a single measurement position was relocated. The average difference between the repeats was 2.6 dB (±1.5 dB), with the only appreciable differences (>1 dB) being found for PAVA systems 3 (5.6 dB) and 4 (6.9 dB).

IV. DISCUSSION

This study shows that members of the public are being exposed to US at levels of around 70–75 dB SPL (20-kHz TOB) from PAVA systems in widely accessed public places such as busy train stations and museums (with yearly footfalls in some cases in the tens of millions). This conclusion is supported by the findings of Mapp (2016, 2017). The

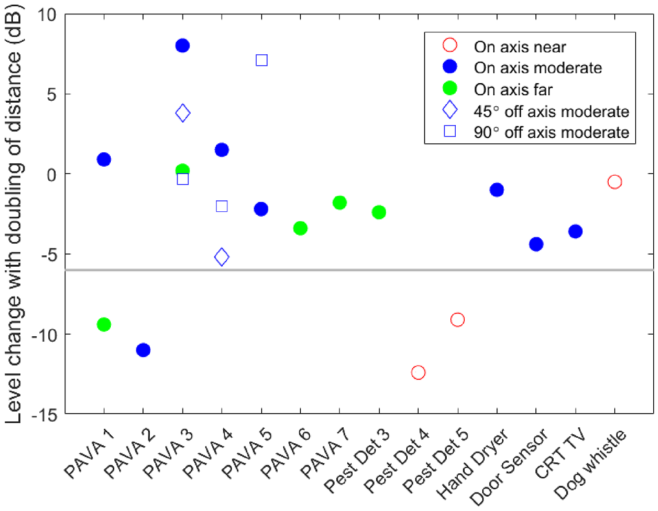

FIG. 4. (Color online) Change in SPL with doubling of the distance from several of the sources, both in front of the source and at difference azimuths relative to the front. A negative number means a decrease in level with increasing distance. "Near" measurements were taken 0.25 and 0.5 m from the source, "moderate" measurements were taken 1 and 2 m from the source (apart from for PAVA system 2, which is at 1.5 and 3 m), and "far" measurements were taken 2 and 4 m from the source (apart from PAVA system 6, which was at 3.75 and 7.5 m and pest deterrent 3, which was at 7.25 and 14.5 m). In anechoic conditions with a point source, a decay in level of 6-dB per doubling of distance would be expected. This is marked with a grey horizontal line in the figure for reference. All levels are for the TOB in which the highest level was measured for the source (see Table I).

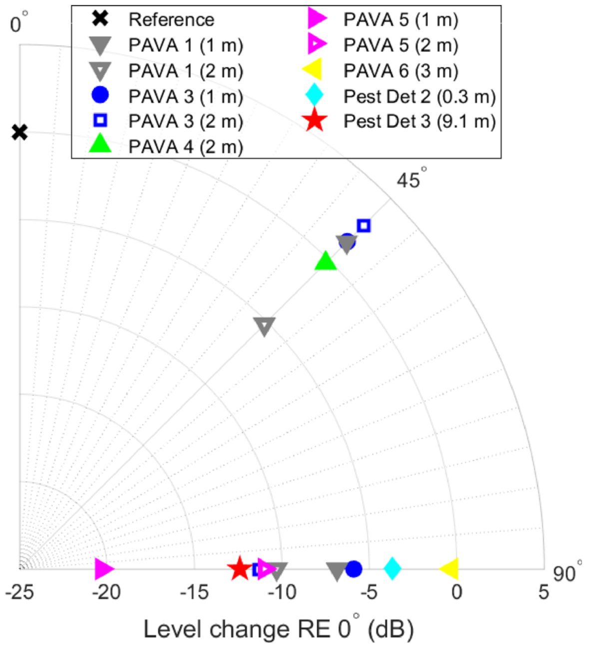

FIG. 5. (Color online) Change in SPL as a function of azimuth for several of the sources. A negative value represents a reduction in level relative to the 0° position in front or on-axis to the source (marked by an "×"). The distance from the source at which the level change with azimuth was measured is shown in brackets for each source in the legend. All levels are for the TOB in which the highest level was measured for the source (see Table I).

results also show that some individuals may be regularly exposed to US at levels of around 85–100 dB SPL (20-kHz TOB) from relatively commonplace devices. In particular, a hand dryer and pest deterrents were found to be capable of producing these levels, usually in public exposure [as opposed to occupational settings: this distinction becomes very important when one compares exposures to guidelines (see below; Leighton, 2016b)]. The most intense US sources identified were pest deterrents (pest deterrents 1 and 2), which produced ∼100 dB SPL (20-kHz TOB) close to the source. This is significantly lower than the 120 dB SPL pest deterrent measured in Tokyo by Ueda *et al.* (2014). Hand dryer 1 produced energy across a range of frequencies with the highest level at 84 dB SPL in the 40-kHz TOB. An ultrasonic cleaner in an industrial setting that produced significant energy at 40 kHz has previously been reported by workers to cause fatigue, buzzing noises and painful whistles, nausea, and headache, which continued for hours after the exposure had ceased (Acton and Carson, 1967). However, this source produced 115 dB SPL at 40 kHz, so was substantially more intense, and workers were exposed to the source for several hours on a regular basis. At very high frequencies (11.3–17.8 kHz), the loudest source measured was hand dryer 1, which produced 80.8 dB SPL (16-kHz TOB). Other sources in this frequency range, which were informally reported by members of the public to be highly annoying, and in some cases to trigger headaches or tinnitus, were much lower, at around 65–70 dB SPL. The door sensor, about which we received only one specific complaint, was found to produce only 42.4 dB SPL (20-kHz TOB).

Tests of repeatability of the measurements showed that most were highly repeatable. However, when relocating the measurement point for one of the PAVA systems, differences between the measurements of up to 7 dB (for PAVA system 4) were found. This is consistent with Mapp (2016, 2017), who found differences of up to 10 dB between repeated measurements. One source of variability that may be particularly problematic for this PAVA system is the difficulty in accurately locating the center of the source [because the loudspeaker(s) was mounted behind a large grill]. Further sources of variability may be the potentially significant changes in the acoustics of the environment created by the large numbers of people moving around the space near to the recording position and the difficulty of measuring from precise locations under these conditions. Furthermore, SPLs within the space may vary even with small changes in measurement position due to the reflections from the ground or objects within the space, which can lead to level enhancements or reductions through constructive or destructive interference with the direct sound. Finally, recordings were made with a 1/2-in. microphone diaphragm parallel to the wavefront at a sufficient distance from the source for the wavefronts to be approximately planar, so that at any given time the pressures across the diaphragm will be in phase. However, as the frequency gets higher, the tolerance allowable in aligning the membrane to the wavefront becomes smaller, and the possibility of introducing error because of phase changes across the sensor increases. For measurements above 23.5 kHz, the wavelength would have been less than the diameter of the diaphragm and, therefore, the reading could have been affected by small changes in microphone orientation to the source. These significant potential sources of variation should be taken into account when assessing the change in SPL with distance and angle for PAVA systems 3 and 4, and raise the possibility that, in some such cases, the maximum levels may have been underestimated.

An important question when assessing the significance of the SPLs measured is whether they are high enough to be audible to members of the public. Hearing thresholds above around 12 kHz are well known to increase rapidly with increasing frequency (see, for example, Lee *et al.*, 2012; Rodriguez Valiente *et al.*, 2014). It is less widely known, however, that there is evidence that, in individuals whose detection thresholds are measurable at ultrasonic frequencies, the fall-off rate decreases markedly above around 20 kHz (Henry and Fast, 1984; Ashihara, 2006, 2007). Ashihara (2007) measured free-field hearing thresholds in 19–25-yr-olds, and found that 29 of the 32 participants had thresholds better than 110 dB SPL at 20 kHz, 25 of the 32 at 22 kHz, half of the participants at 24 kHz, and 3 out of the 32 at 28 kHz. No participants measured by Ashihara had thresholds better than 100 dB SPL at 30 kHz (the highest level that could be produced by their equipment). In a large study of hearing thresholds across different age groups, Rodriguez Valiente *et al.* (2014) found an average detection threshold at 20 kHz (around the peak frequency for the majority of sources measured in this study) of 65 dB SPL in 5–19-yr-olds and 85 dB SPL in 20–29-yr-olds. They estimate that 5% of 5–19 and 20–29-yr-olds are able to hear sounds at 30 and 35 dB SPL, respectively, at 20 kHz. It should be noted that the measurements by Rodriguez Valiente *et al.* were made over headphones, and average detection thresholds with the headphones used differ significantly from measurements in free-field. At 16 kHz (the highest frequency at which there is a standard reference level for free-field and the headphones used), the free-field equivalent level is 12 dB lower. These audiometric measurements suggest that nearly all of the US sources measured in this study would be clearly detectable for an average 5–19-yr-old, with pest deterrents 1 and 2 being ∼45 dB, and two of the PAVA systems being ∼20 dB, above the average threshold. Indeed, even the weakest US source measured (the door sensor), would be expected to be audible to some 5–19-yr-olds.

At 14 kHz, Rodriguez Valiente *et al.* (2014) measured average thresholds of 29 and 27 dB SPL for 5–19 and 20–29-yr-olds, respectively. All of the lower frequency sources measured, with peak frequencies around 14 kHz, would therefore be comfortably audible for the average 5–29-yr-old (with the dog whistle being around 40 dB above the average threshold). Indeed, even for the group of 40–49-yr-olds, whose average threshold at 14 kHz was 55 dB SPL, most of these sources measured would be expected to be audible.

Given that many of the sources measured in this study are far above the average detection threshold for young listeners, the next important issue is whether they are safe. One way to assess this is to compare exposure levels to existing safe listening guidelines. As has been highlighted by Leighton (2016b), guidelines for safe sound level exposure in this 20 kHz band differ markedly (ranging from 70 to 140 dB). This extreme divergence stems largely from the lack of a clear evidence base (for reviews, see Lawton, 2001; Leighton, 2016b). In the UK, the Health and Safety Executive (HSE) defines limits for the 8-h equivalent continuous noise level (Leq) with an A-weighting applied (for employees). The HSE "lower exposure action level" (the level at which the employer has to take some action such as offering hearing protection) is an 8-h Leq of 80 dBA, which corresponds to 89.3 dB SPL at 20 kHz and 85.3 dB SPL at 14 kHz for the Z-weighted recordings made in this study. For every halving of exposure time, 3 dB is to be added to the maximum level (to retain a constant intensity), so that the lower exposure action levels are, for example, 9 dB higher for one hour of exposure. The United States Department of Labor (USDL) Occupational Safety and Health Administration (OSHA, 2011) recommended a MPL of 90 dBA (99.3 dB SPL at 20 kHz, with 5 dB added for every halving of exposure time) for 8 h of exposure and the American National Institute for Occupational Safety and Health (NIOSH, 1998) recommend a maximum exposure level for 8 h of exposure of 85 dBA (94.3 dB SPL at 20 kHz, with 3 dB added for every halving of exposure time). Both the UK and United States regulations are designed to avoid the risk of noise-induced hearing loss, not symptoms such as annoyance. None of the devices measured in this study clearly breached the UK HSE lower exposure action level or the USDL or NIOSH exposure limits for the durations that workers are likely to be exposed, unless they were working for long periods directly in the vicinity of devices, such as the pest scarer. However, these guidelines apply only to exposure for workers and do not specify exposure limits for members of the public (which would include, for example, infants) who may be expected to be exposed to the devices measured in the current study, which are publically available or mounted in public places. Note also that, as previously stated, these guidelines for US are based on very little evidence.

Several guidelines, which consider exposure to members of the public (not just workers), recommend a more cautious maximum exposure level. For example, the World Health Organization (Neitzel and Fligor, 2017) and United States Environmental Protection Agency (USEPA, 1974) both recommend an exposure limit of 75 dBA for 8 h and an 87 dBA maximum for exposure of 30 min (corresponding to 84.3 and 96.3 dB SPL at 20 kHz, respectively). The International Non-Ionizing Radiation Committee of the International Radiation Protection Association (INIRC-IRPA, 1984), recommend a maximum of 70 dB SPL in the 20-kHz TOB for a continuous exposure up to 24 h a day for members of the public and 75 dB SPL in the 20-kHz TOB for continuous occupational exposure of up to 8 h (with 3 dB added for each halving of occupational exposure time). INIRC-IRPA entitled this guideline as "interim" because it was based on such sparse evidence, but since 1984 it has not been revisited by them. INIRC-IRPA argue that effects such as annoyance and stress must be considered when setting limits, and note that caution is required when setting exposure limits in this frequency range because of the limited evidence about the safety of exposure. Pest deterrents 1 and 2 breach these more cautious limits for people who are nearby even for relatively short periods.

Little is known about the dependence of many of the symptoms that have been linked to VHFS/US, such as headaches and tinnitus, on the physical properties of sound. However, some studies have looked at the dependence of annoyance and related sensations on frequency, bandwidth, and level. Annoyance is composed of several more elementary sensations, including roughness, tonality, and sharpness, and is also influenced by higher level psychological and emotional factors such as perceived control over, and predictability of, noise (Fastl, 2005). "Sensory unpleasantness" is closely related to annoyance, but is defined so as not to be influenced by higher level psychological and emotional factors, such as perceived control over the source (Zwicker and Fastl, 1999; Kurakata *et al.*, 2013). When loudness is kept constant, sensory unpleasantness has been found to increase with frequency for tones up to 18 kHz (Kurakata *et al.*, 2013) and to be stronger for tones than noises (Zwicker and Fastl, 1999; although this latter work did not include VHFS). The audible VHFS/US sources measured in the present study, which were predominantly tonal, are therefore expected to be more annoying and unpleasant than lower frequency sources with a similar loudness. Furthermore, Aazh and Moore (2017) reported evidence that patients suffering from hyperacusis—the inability to tolerate sounds that are not uncomfortably loud for most people—may be most sensitive to sounds at higher frequencies. Aazh and Moore only measured hyperacusis for sounds up to 8 kHz, and further work is required to establish whether hyperacusis continues to become more acute for VHFS.

This study measured the SPL produced by a number of sources, which have been reported by some members of the public to cause adverse subjective effects, *in situ* at realistic listening positions. Pest deterrents (pest deterrents 1 and 2) were found that produced levels of up to around 100 dB SPL in the 20-kHz TOB, a hand dryer (hand dryer 1) produced 81 dB SPL (20-kHz TOB), and some PAVA systems in busy public places produced up to 76 dB SPL (20-kHz TOB). Other VHFS sources measured produced levels far in excess of detection thresholds for young listeners. Nearly all of the devices measured that produced VHFS and US are likely to be clearly audible to young people. Further work is needed to establish whether the sound levels produced by these devices are capable of producing some of the subjective effects—such as tinnitus, nausea, and headaches—that have been reported.

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