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5th International Conference on the Effects of Noise on Aquatic Life

Den Haag, The Netherlands
7-12 July 2019

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The Effects of Noise on Aquatic Life

AN2019: Plenary Talk (Thursday)

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Analogies in contextualizing human response to airborne ultrasound and fish response to acoustic noise and deterrents

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In assessing the impact of sound on aquatic life, or its potential to guide fauna away from hazards, there is reliance on decades of human audiology, for example by adapting tests such as behavioral audiograms and Auditory Evoked Potentials.

However, now that human audiology has translated over decades from research laboratories to the high-street hearing-aid dispenser, we might forget the underlying challenges that human audiology overcame, and which face its aquatic analogue because it is still in its infancy.

A major challenge of researching effects of sound on fish comes from sparsity of data. One aspect of human audiology that shares this characteristic is the effect of Very High Frequency sound/ultrasound in air on humans. Their similarities will be discussed in terms of the difficulties associated with: lack of appreciation of the complexities of the sound field; lack of recognized calibrations and measurement procedures; reliance on the concept of a 'typical' subject based on an average; reliance on data from too few subjects; insufficient appreciation of group effects; reliance on a tacit assumption of an assumed mapping between threshold for hearing and threshold for behavioral/adverse effects; the tension between field and laboratory observations; and confusion caused by inexpert reporting.

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1. INTRODUCTION

This paper is a write-up of a plenary talk at the 2019 "Effects of Noise on Aquatic Life" conference (Den Haag, The Netherlands, July 7-12, 2019), the unusual topic having been suggested to the main author by the organizing committee for its ability to provide an unorthodox perspective. This is therefore not a review of two fields, but an exploration of whether a multidisciplinary perspective can bring benefits to either. As such, each section will end with a suggested possible 'takeaway'.

The 1940s saw the first reports of so-called 'ultrasonic sickness', the term giving the unfortunate impression of an etiology in injury or illness when no such causal link had been demonstrated[1]. Rather, 'ultrasonic sickness' grouped a set of symptoms reported by workers (ear-ache, headache, excessive fatigue, irritability, nausea, feelings of fear), and without evidence of causation, a connection was made to ultrasound exposure that was thought to be common amongst that group. The same could be said of the claims of adverse effects suffered by US Embassy staff in Cuba[2-6] (Section 10).

These examples illustrate how poorly the topic has progressed[7] despite decades of research and national/international guidelines. The research was hindered by[1,8,9]:

- lack of understanding of the complexities in acoustic fields by experts in human response (Section 3);
- lack of understanding of the complexities in ultrasonic fields by experts in audio-frequencies, who simply extrapolated (Section 3);
- lack of recognized calibration standards and measurement procedures (Section 4);
- reliance on results from a number of subjects (which are then averaged to represent a 'typical' member of the species) that is too small to understand the variability in the inter-subject range of response (Section 6) or to predict the response of an individual who has yet to be tested (Section 5);
- insufficient appreciation that a group experiencing adverse effects might self-reinforce, providing a cohort response atypical of measured individual responses (Sections 7 and 10); and
- reliance on a tacit assumption of a predictable mapping between threshold for hearing and threshold for behavioral/adverse effects (Section 8).

The above points related to the measurement of Very High Frequency sound and Ultrasound (VHF/US) and its impact on humans, also relate to the response of aquatic fauna to audio-frequency sound. To keep within the scope requested by the organizers for this plenary address, ultrasound is only introduced in the context of its effects on humans, and any effect on fish is excluded; and although infrasound can be detected by many fish, infrasound is excluded from discussion here for both humans and fish, a helpful limitation because perhaps the main problem of any treatise of ultrasonic effects on humans is the urge by readers, media, and sufferers to conflate ultrasound with infrasound.

A retrospective of the effect of airborne-VHF/US on humans, when considering the effect of sound on fish, contains two parallels:

- Both draw on aspects of human audiology in the traditional frequency range (i.e., 224-8910 Hz; throughout, this paper will use upper/lower limits of the relevant one-third-octave band (TOB) because[8] many exposures are tonal). Both build on the same predecessor, and consequently face similar challenges when the assumptions underpinning inherited practices are stretched. Both suffer from sparse datasets, whereas the predecessor (human audiology) is well-sampled enough to underpin millions of diagnostic and corrective measures; and
- A modicum of empathy assists experimental design, methodology, recruitment and interpretation, and underpins human audiology; but is difficult to access for experimenters testing fish responses, or the response of a sensitive human to a radiation the experimenter cannot feel or predict (given the huge range in human response to VHF/US; see Section 6).

Recent decades have shown both an increase in anthropogenic airborne-VHF/US sound[10-12] (Figure 1) and in anthropogenic aquatic sound (from shipping, dredging, sonar, and work on infrastructure and energy supply such as seismic surveys, pile driving, turbines, and the laying of cables and pipes).[13-19] Both produce *involuntary* exposures, so this article will concentrate on public airborne-VHF/US exposures (Table 1),[20-26] rather than occupational[27,28]. Public and occupational exposures differ because, in the workplace, people know they are exposed, their medical history is known and health monitored, the duration and levels of exposure are controlled, and hearing protection can be used. The levels in Table 1 are high (Figure 2), given that the only guidelines[29] for Maximum Permissible Levels (MPLs) for public exposure are 70 dB re 20 µPa SPL for 17.8-22.4 kHz, and 100 dB re 20 µPa above 22.4 kHz (for continuous exposure, the assumption that must be made for public exposure unless the source is deactivated for a time).

A perspective encompassing the two topics (the effects of sound on fish underwater and of airborne-VHF/US on humans) will be discussed in terms of the difficulties that arise: when the complexities of the sound field are not appreciated (Section 3); by lack of recognized calibrations and measurement procedures (Section 4); by reliance on the concept of a 'typical' subject based on an average (Section 5); reliance on data from too few subjects (Section 6); insufficient appreciation of group effects (Section 7); reliance on a tacit assumption that there exists a reliable mapping (upon which predictions for an untested individual can be based) between threshold for hearing and threshold for behavioral/adverse effects (Section 8); the tension between, and the complementary benefits of, field and laboratory observations (Section 9); and the confusion caused by inexpert reporting (Section 10). The paper ends with Conclusions (Section 11).

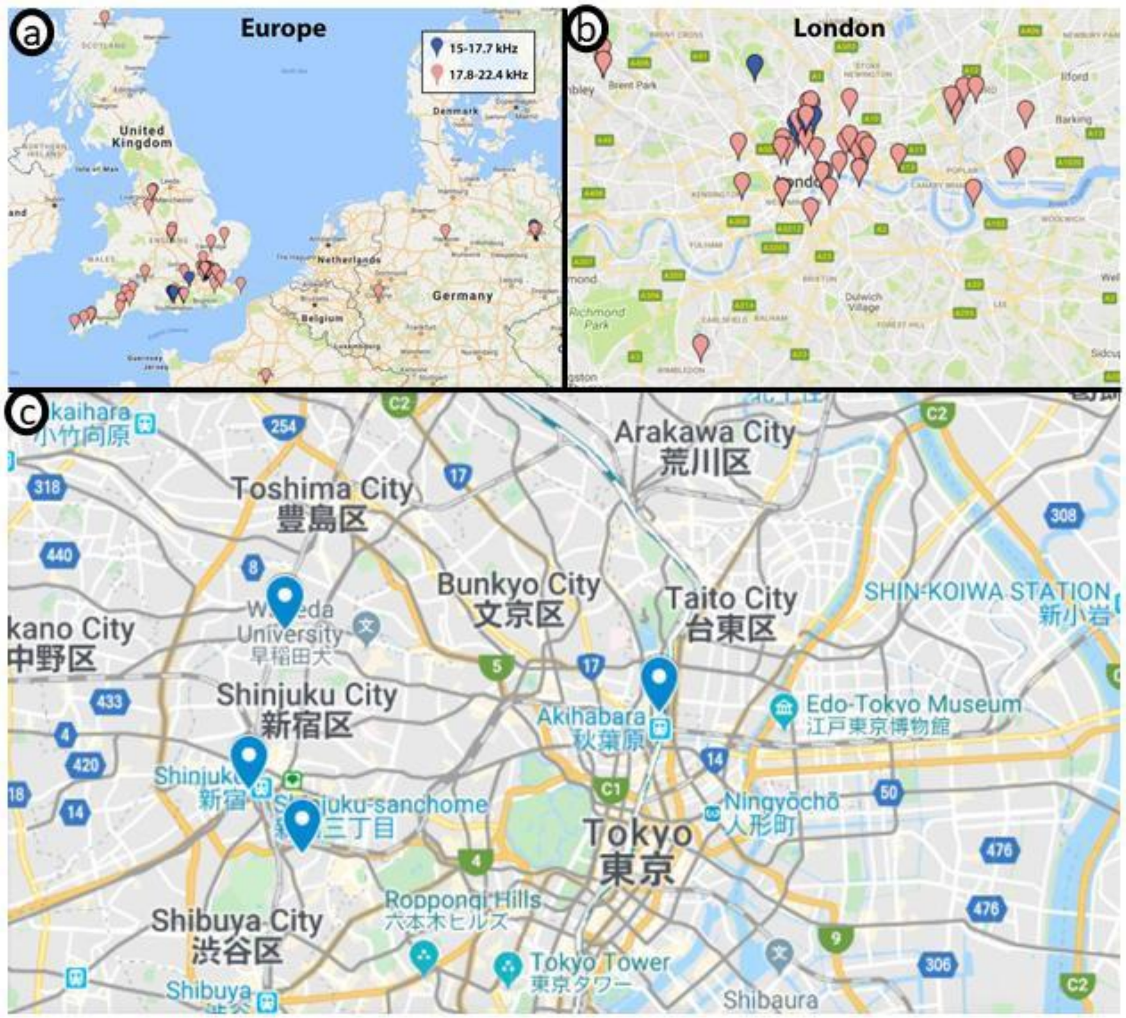

Figure 1. Maps showing the location of sources of Airborne-VHF/US identified by members of the public using smartphones in (a) Europe and (b) London (reproduced from Fletcher et al.[10]) and (c) Tokyo (Google Maps, 2017) (reproduced from Martin[11]). In generating the red markers (a) and (b), Fletcher et al.[10] used the criteria that, for a source to be included in (a) or (b), 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. Map (c) was generated by a different author,[11] the sources being located by blue inverted tear-drops. The limited sample rate of smartphones means that higher frequency sources could not be recorded in any of these maps.

Table 1. Examples of accidental or deliberate exposures from commercial devices

Accidental or deliberate exposure?[1]	**Commercial source**	**Frequency**	**dB levels (re 20 μPa SPL) at the possible position of the human ear (flat, Z-frequency weighting)**	**Reference for measurement**
Accidental	pest deterrents[1,10,20]	~20 kHz	120 dB right under the device at a 1.6 m	Ueda *et al. (*2014)[21,22]
			90 dB at 14 m range	
Accidental	Public-Address-Voice-Alarm[1,23,24]	~20 kHz	76 dB	Fletcher *et al*. (2018)[10]
Accidental	hand-dryers	~40 kHz	84 dB	Fletcher *et al*., (2018)[10]
Deliberate	acoustic spotlights	~20 kHz	53 dB	Dolder *et al*. (2018)[25]
		~40 kHz	118 dB	
Deliberate	haptic feedback	~40 kHz	155 dB	Liebler *et al*. (2019)[26]

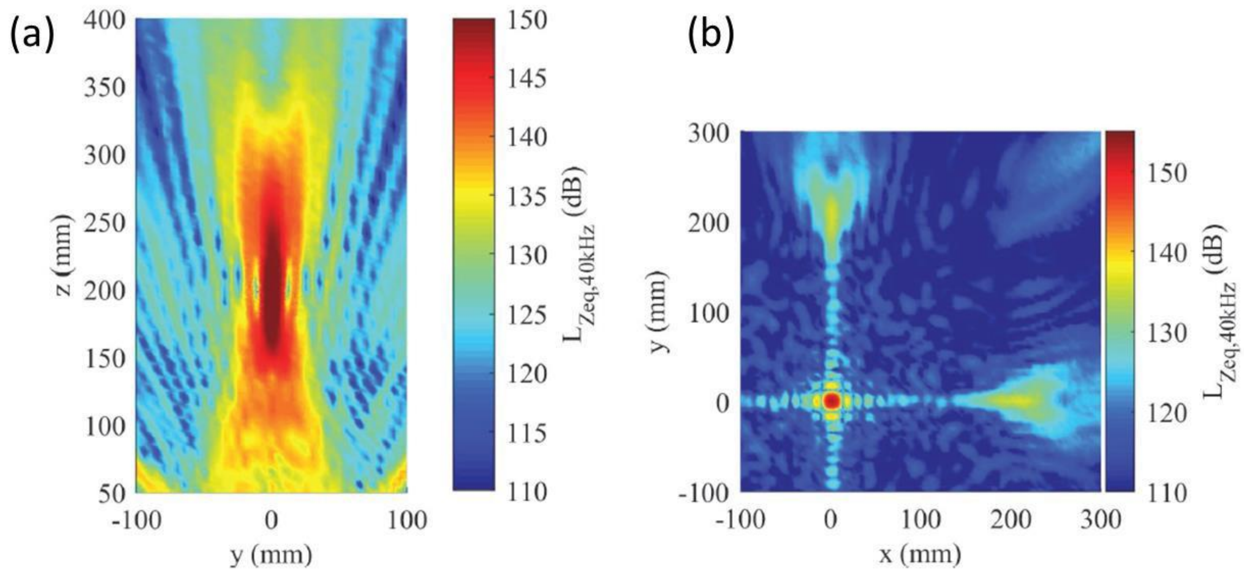

Figure 2. The spatial distribution in a (a) vertical and (b) horizontal plane through the focus where the human is meant to interact with an ultrasonic field to produce haptic feedback (such that (b) is measured at z=200 mm) at maximum setting, taken at the Physikalisch-Technische Bundesanstalt (PTB) using a 1/8" 40DP microphone (figure taken from Liebler et al.[26]).

2. WHO IS OF INTEREST, AND WHY?

What members of the population are we seeking to protect? The question relates directly to whether we know the inter-subject variability and can rely on some 'average' representation of the species for regulation and guidance, and calculate how many subjects we must include in a study, based on known legacy data (Sections 5 and 6). If the legacy data never included the most sensitive outliers (section 7), then they are not accounted for in the guidelines we construct and power analyses we use to design experiments. Whether this matters, depends on whom we are seeking to protect.

For fish, we protect populations. Given that controls for public exposure to Airborne-VHF/US are in their infancy, in terms of legal protection we are forced to look to the controls that have been placed on occupational exposure. German workplace law effectively states that protection must be given to all workers from all possible hazards[1,30,31]. This would require knowledge of the individual or a cautionary approach, protecting the most sensitive (difficult given wide inter-subject variabilities; Sections 5 and 6). In contrast, in the UK the Health and Safety at Work Act 1974 requires employers to protect their employees and the public, and employees to protect themselves and each other, by the principle of 'so far as is reasonably practicable', explained as follows by the UK Health and Safety Executive[32]: 'In other words, an employer does not have to take measures to avoid or reduce the risk if they are technically impossible or if the time, trouble or cost of the measures would be grossly disproportionate to the risk'.

Why might we measure the audiograms for humans or fish? Many current studies of fish hearing aim to understand how ambient noise may impact fish or may be used for fish guidance. The purpose might be to avoid acute impacts, e.g., injuries such as hearing threshold shifts; or to understand the impact of chronic exposures; or to develop a behavioral guidance system. To understand chronic impacts, one needs direct measurements, or a reliable mapping from hearing sensitivity to chronic impacts. Data of hearing sensitivity from a sufficiently large cohort to enable reliable predictions of sensitivity of a similar cohort, might lead to the construction of a weighting based on fish hearing (F-weighting). Research into behavioral changes in response to sound might seek to link those changes to effects in important functions (predator avoidance, mating, or feeding), which in turn impact survival rates. Fish guidance seeks a purely behavioral response.

The role of acoustics, and the drive to understand fish hearing, is different in each of these areas, but its evolution parallels in some ways what happened over the last 7 decades in the study of the human response to airborne-VHF/US. With the current involuntary exposure of the public, in their millions, to low-level airborne-VHF/US (Figure 1), interest is in the minority who, at the low amplitudes of current VHF/US public exposure that appear to leave the majority unaffected, might exhibit the effects that have typically the lowest thresholds for excitation (discomfort, annoyance, and failure to concentrate and perform tasks, i.e., some of the so-called 'subjective' effects). However international guidelines for exposure above the 20 kHz TOB set MPLs that are not based on inducing such 'subjective' responses, but instead are based on temporary hearing threshold changes. Such MPLs therefore run the risk of permitting public exposures that induce these 'subjective' effects. Similarly, some literature states stimuli were presented well above the hearing threshold of the fish, which also creates potential for mismatching criteria[33]. This emphasizes the need to document experimental methodology more thoroughly, and perhaps apply more rigorous experimental procedures, particularly since acoustic deterrents have been developed with varying success[34]. Frequency weighting functions for fish have been discussed by researchers[35], including the "F-weighting" adapted from "M-weighting" in cetaceans and pinnipeds. An F-weighting must be a population level (Section 5), probably covering multiple species, and be useful for assessing potential impacts of sounds. Once established, it can be hard to challenge limitations in widely-used methodologies. For example, A-weighting was not designed to be used above the 20 kHz TOB, yet is still used by some researchers when expressing measured levels of VHF/US. The fact that A-weighting is thought to mimic the frequency response of a typical human highlights this problem (Section 5), because as stated above, for public exposures we are interested in the thresholds of a significantly more sensitive subset, in a frequency range where there is far greater inter-subject variability in hearing thresholds for those with 'normal' hearing than there is below 8 kHz.

3. LACK OF APPRECIATION OF THE COMPLEXITIES IN THE ACOUSTIC FIELDS

The recognition of the need for increased understanding of, and capability to measure and model, the marine environment, has over the last century been driven by a defense imperative, notably for the use of sonar in submarine detection, dominated in the second half of the 20th century by the need to detect nuclear submarines passing under the North Polar icecap during the Cold War. As military engagements moved to the littoral waters in the 1990s (which for the defense purposes under discussion, roughly means less than 20 m deep), recognition increased of the need for expertise in shallow water acoustics. The high levels of man-made underwater signals generated for defense, for seismic and civil engineering operations, and to assess the environmental impact of anthropogenic activities, led to a growing appreciation of the need to protect aquatic fauna from the adverse effects of anthropogenic noise, with an initial focus on marine mammals[36], then fish[37], and most recently benthic[38], species (ironically in reverse order of the ability of the species to relocate away from regions of sound that might cause adverse effects). This was tackled through modeling, complementary tank and field measurements, and impact assessments. As such awareness increased, the knowledge and capability gaps surrounding the acoustics of shallow waters (for this article, roughly less than 60 m deep) where much of the anthropogenic noise was concentrated, became more apparent.

Figure 3. (a) A channelized concrete levada on the island of Madeira. (b) The arrow shows the tailrace of the Igarapava Dam, Brazil.

Initially the off-shore marine environment was the focus of study, but in recent years the additional complexity of the sound fields in coastal and inland waters have been appreciated as an issue that could hamper progress[39], prompting increased interest in estuarine and riverine freshwater environments[40-43].

Freshwater systems are extremely variable, shallow watered (sometimes < 1 m depth) and highly modified environments with banks and riverbeds that introduce a wide range of sediment properties, flow rates, turbulence and bubble populations. Here, the influence of other abiotic factors (e.g., wind) can create a multiple boundary environment with the potential to influence sound propagation, and subsequently the pressure/ particle velocity relationship. Freshwater fishes are one of the most threatened groups of vertebrates, and the loss of biodiversity in fresh water exceeds that observed in both terrestrial and marine environments[44,45]. Freshwater fishes are one of the great natural resources of the world, but anthropogenic activities have adversely affected aquatic ecosystems and many species are threatened with extinction. Freshwater systems can be subject to significant manmade infrastructure, such as fish passes, dams and weirs[46]. Indeed, on Madeira (a mountainous island measuring 57 km by 22 km at its widest point), freshwater fish are found in the levadas, a 2170 km long network of mainly open channels dating from the 15th century. Figure 3a shows a typical concrete-lined levada, in which fish were observed, that would produce strong wall reflections in channels having dimensions similar to those of laboratory flumes and tanks. The shallow depths in Figures 3(a) mean any fish would be in close proximity to the nearly pressure-release water/air interface at the top of the water column, which will hamper the propagation of sound down channels of less than roughly a quarter of a wavelength depth, although of course such channels can contain locally strong sound sources (e.g., construction and agriculture noises; sound associated with flow when water speeds are high). The arrow in Figure 3(b) shows the tailrace of a dam in Brazil. When turbines are taken off-line for maintenance, fish can enter them. When the turbines are restarted, fish can be killed in such huge numbers that the mortality is measured in terms of weight, which can be tons of fish per restart event[47,48]. Acoustic (and other[49]) deterrents could well be considered here to stop fish entering the turbines from downstream during maintenance, or at water extraction points in levadas of the type shown in Figure 3(a). A tank test of such a deterrent might produce an acoustic environment more akin to that seen at these two field locations, than would a natural open-water test.

This complexity of the sound field (with the aforementioned strong scattering and propensity for inhomogeneity, as seen in fish tanks and engineered waterways) also maps into the study of airborne-VHF/US. Even the assumption that a near-horizontal ray, on leaving the measured domain, might never return to it (common in deep-water acoustics, and in in-air anechoic chambers at lower frequencies) becomes questionable as the domain translates to coastal and inland waters, and to in-air anechoic chambers as the frequency increases.

When studying airborne-VHF/US, historically (and, in many cases, even today) the researcher is making measurements with instrumentation that was designed for use with longer wavelengths; consequently, the introduction of the human subject is considered not to have a significant impact on the field. As we approach the lower limit for ultrasound (17.8 kHz, Leighton argues[8]) the acoustic wavelength at ~2 cm approaches the size of the important scattering bodies (such as the pinna; Figure 4), so that the ability to reproduce measurements of sound fields becomes increasingly difficult (particularly when a given microphone is mounted on different stands etc.). The presence of the observer, be it the person or the instrument, can have an appreciable effect on the sound field. It therefore becomes more challenging to reproduce stimuli to a human test subject in a sound field at these higher frequencies.

For underwater studies with fish, the subject can also have a large impact on the sound field for an entirely different reason. Many fish contain gas-filled swim-bladders that resemble acoustic bubbles and alter the sound field. A school of fish can effectively reduce the speed of sound through the school to the point that the wavelengths become much smaller than that in fish-free water[52]. Just as with Airborne-VHF/US, the wavelengths can become small relative to the sensors being used. Not only are the scattering patterns more complicated as the wavelength decreases, but in addition the sensing element of the apparatus becomes large relative to the apparatus, so that the phase of the signal may change over the sensing element. For these reasons, it is crucial that attention be paid to standard measurement procedures and traceable, reliable calibrations[7,53]. This is the topic of the next section.

Takeaway: The question here is not whether we appreciate the complexity of the sound fields we measure today – this is well-documented – but whether the legacy studies on which we base our received wisdom did. We need received wisdom in order to progress and avoid 're-inventing the wheel', but such received wisdom was built pragmatically with the capabilities of the day, and should be periodically questioned.

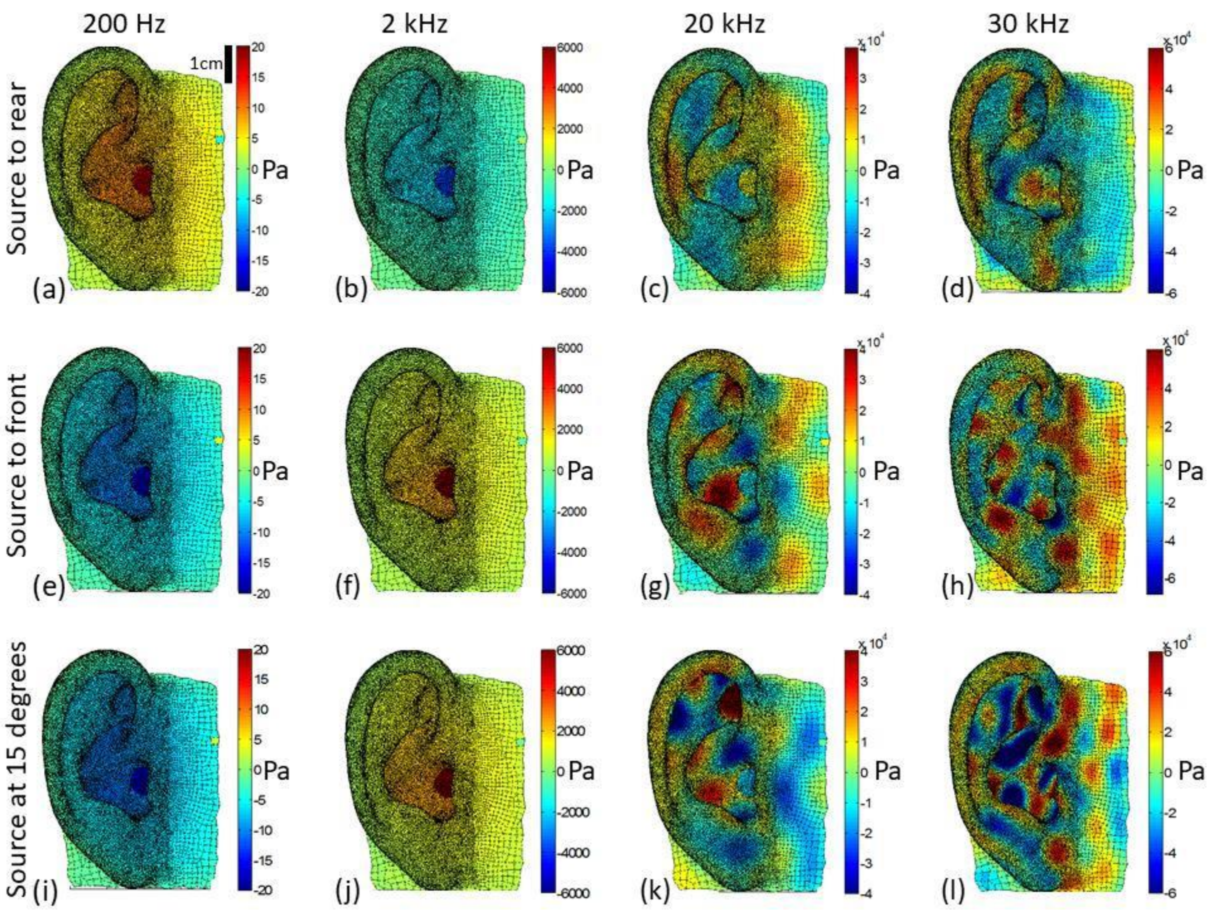

Figure 4. The real part of the scattered pressure (in Pa) from a point source placed 1 m from the opening of the ear canal, and in the same horizontal plane as it (calculated using Boundary Element Method optimized for High Performance Computing after the manner of Grace et al.[50]). Panels (a)-(d) [top row] are when the source is directly behind the ear. Panels (e)-(h) [middle row] are when the source is directly in front of the ear. Panels (i)-(l) [bottom row] are when the source is angled 15º outwards, away from the front position. The columns from left to right are for increasing source frequency: 200 Hz [(a),(e)]; 2 kHz [(b),(f)]; 20 kHz [(c),(g)]; 30 kHz [(d),(h)]. The point source has a volume velocity amplitude of 1 m^3s^{-1} for all plots, and this causes the acoustic pressure naturally to increase with frequency (because there is a scaling factor between them that is proportional to frequency). For simplicity the flesh is assumed to be acoustically rigid. The geometry of the pinna was adapted from Kahana and Nelson[51] with an added ear canal depth of 2.5 cm. The ear canal in this model is straight so that the eardrum is visible in every image at the base of the ear canal. Human ear canals contain a bend, although in some individuals this is less pronounced than in others. Reproduced from Leighton[1], Copyright 2016 The Royal Society.

4. LACK OF RECOGNIZED CALIBRATIONS AND MEASUREMENT PROCEDURES

The previous section introduced the difficulties in extrapolating our experimental expertise at audio-frequencies to higher frequencies. There are a host of other issues. First, the complexity of the environmental sound fields, for both VHF/US and fish acoustics, leads to the need for laboratory-controlled environments. For airborne acoustics, the time-tested environment would be an anechoic chamber: but what anechoic chamber is certified[9] to 30 kHz? Few chambers have any certification above 20 kHz. This means that any measurements performed above the certified test range of the chamber may be contaminated by unexpected reflections or noise. Assuming one can find an anechoic chamber certified up to the desired frequency, the measurement standards may fall short. A 25 kHz US source could have a primary lobe that falls between measurement positions (specified[54,55] by standards as a pattern on a sphere encompassing the source), and so be missed through spatial under-sampling, even when using the extended 40 microphone option specified in Annex D of Ref. [54].

For fish audiology, the general laboratory environments are tanks, which come with the advantages of generating controlled conditions and using fish with known histories, but introduce acoustic complexities (and other confounding factors) not encountered in most natural environments, and so are seen as a preparatory step to close knowledge gaps prior to field work. However, the complexities of their acoustic fields (with strong wall reflections, standing waves, waveguide characteristics etc.) can be closer to engineered freshwater environments such as levadas, fish passes, tailraces etc. (Section 9; Figure 3).

Although there are some exceptions where acoustic mapping is done[33, 56-57], most experiments with fish using tank tests run the risk of sampling the acoustic field at too few spatial points to capture the complexity of the field, reporting perhaps one power spectral density of acoustic pressure and/or particle motion as an average, with measures taken at a small number of points (sometimes only in the center of the tank). This does not provide insight into the complexity of the sound field that fish could be experiencing over the locus of their swim-path (which can vary significantly) – and could lead to some misinformed conclusions. Furthermore, it is recognized that some species react more to particle motion than acoustic pressure[58-63], but apparatus for measuring the former is currently less available than the sensors of the latter. The particle motion can be estimated from measurements of the sound pressure field. However, this does require that the phase of the pressure field is recorded as well as it is amplitude and that measurements of the pressure field are taken at a sufficiently fine spatial resolution.

Standards for measuring equipment can be misleading unless investigated closely. For instance, we may read of a paper where adverse effects were or were not observed in humans exposed, at a given Z-weighted dB re 20 µPa, to an acoustic field in the 20 kHz TOB. But in drawing conclusions as to the threshold for such an effect, how many of us would be aware that, whilst the performance acceptance limits of the relevant standard state that a Class 1 sound level meter at 1 kHz should be ±1 dB, they are from +3 dB to −∞ dB at 20 kHz. This means that the sound level meter could be capable of severely underestimating signal amplitudes in the 20 kHz TOB and still meet the acceptance criteria of the standard. Indeed, at these high frequencies the guidelines contain ambiguities that have been shown[25] to allow a given fixed output of real world devices to either exceed or not the MPLs, depending which side of the ambiguity one opts to use.

In contrast to the regime of short wavelengths outlined in the preceding discussion, when used in the aquatic environment acoustic instrumentation is often well within its 'comfort zone' in terms of the wavelengths and frequencies for which it was designed. Nonetheless, the processes are still open to question, in need of validation and standardization if one is to compare between studies. To take just one example (Section 6), there are no standards for the allowable noise exposure for fish (either prior to or during a noise exposure experiment, or in hatcheries from which one might procure fish for experimentation). To appreciate how the absence of standards might affect research in aquatic acoustics, consider how much effort has gone into noise control in classrooms, and yet how that still leaves us with a capability gap when dealing with higher frequencies. Specifications[64] for classroom noise in the UK only mandate noise levels against a calibrated signal up to the 8 kHz TOB, because they specify use of a class 2 sound level meter which, at frequencies of 10 kHz or greater, has acceptance limits of +5 and −∞ dB (the specification in the 8 kHz TOB being ±5 dB).[65] These guidelines, and a range of others, focus on the frequencies perceived to be important to understand speech in background noise, and progressively less attention is paid as one moves to higher frequencies.

Therefore, even for human audiology in the traditional range of 250-8000 Hz, for which a plethora of standards for instrumentation, calibration and procedures have built up over the last century, problems occur through unrecognized uncertainties. Indeed, it is possible to overlook important science when drawing up standards, leading to errors that become embedded and difficult to remove because the infrastructure around standards often responds only slowly to outside pressure. For example, in 1953 Corliss *et al*.[66] reported a simple frequency-dependency that occurs in normal bone-conduction threshold tests. Margolis *et al*.[67] noted how neglect of this feature in subsequent decades, by successive standards committees, has led to a persistent error in the standards, which has resulted in practitioners observing apparent hearing loss where none exists. This problem has not been addressed.

In these examples, accepted practice, established over decades and taught without question, may be at times unreliable for the frequency range for which it was intended, and certainly has the propensity to become unreliable when translated to the new regime of higher frequencies. Even without entering the ultrasonic range (>17.8 kHz)[8], in the sonic regime where instrumentation is thought to be well understood, measurement procedures are well-regulated and substantial investment has been made in facilities enabling data gathering on humans for a century, our understanding is not enough to predict an adverse response in an individual human, even if it was a human for whom we have conducted full clinical audiological testing in the normal range of frequencies up to and including the 8 kHz TOB. Data up to the 8 kHz TOB would not allow us to predict the behavioral responses of the two individuals highlighted[68] in Figure 5 if they were exposed to a strong 16 kHz signal. To what extent would Figure 5 give us additional information for this task? There are clues in it, but we must ask ourselves to what extent does the audiogram predict other (e.g., adverse) responses, and to what extent does it matter if the same spectral content is transmitted to the individuals as band-limited white noise, as a chirp, as music or a warning call (for fish or humans)?

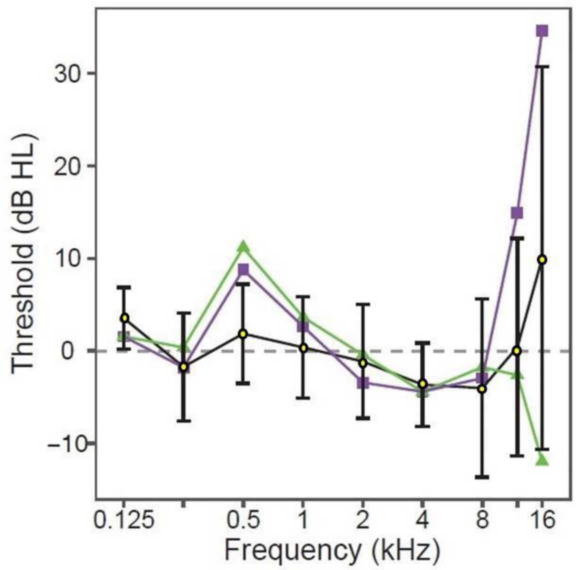

Figure 5. (color online) Data from Plack et al.[68] show (yellow circles with black outline) the mean hearing threshold as a function of frequency for a group of listeners (age range is 19-39 years) who were all classed as normal-hearing on the basis of standard audiological testing. The error bars show +/- 1 standard deviation. The purple squares and green triangles show the data for two listeners who have very similar threshold up to 8 kHz, but markedly different thresholds above 8 kHz.

International quality standards for measuring procedures do not yet exist[69] for fish audiograms, although Halvorsen *et al*.[70] reported on the start of a programme to establish these. There is a clear need for standardization of test signals and protocols for fish measurements, so that direct comparisons can be made. However, the methodologies used to date are diverse. Behavioral studies exhibit a variety of methods and conditioning types, some of which are species specific. In addition, there is no standard procedure on the Auditory Evoked Potential (AEP) measurements. For example, Radford *et al*.[71] used a tone burst of 10 ms duration with a 2ms rise–fall time gated through a Hanning window, whilst Mann *et al*. [72] reported a 50 ms tone burst gated through a Hanning window. The choice of these values is stated but not explained. Additionally, in some cases the fish is partially[72] submerged whilst in others it is completely[73] submerged. It is entirely possible that the different methodologies have led to large variation in the measured hearing thresholds. For example, for goldfish (*Carassius auratus*) Ladich and Fay[74] find, in the literature they examined, a 60 dB range (at some frequencies) for behavioral audiograms and ~30 dB for AEP. They note that the AEP audiogram (median values of the literature they used) is approximately 10 dB higher than the behavioral audiogram up to 1000 Hz, the trend being reversed at higher frequencies. They argue the reasons for this are '*explained by the fact that it is difficult with the AEP technique to create short tone bursts at lower frequencies with good precision in the frequency domain. Short tone bursts with a greater rapidity of onset results in a greater efficacy at generating AEPs at higher frequencies*'. At lower frequencies the proposed explanation suggests that '*Detection thresholds in behavioral studies have been shown to be higher when signal duration decreases in goldfish (Fay and Coombs 1983)[75] and in Atlantic cod [Gadus morhua] (Hawkins 1981)[76]*'. Considerable research has been undertaken in human audiology over the years, in order to obtain the clearest threshold information from ABR testing by optimizing the stimulus and collection parameters. Sample sizes have been sufficient to create confidence intervals for ABR hearing thresholds when compared with behavioral thresholds. These vary according to frequency, hearing level and maturity of the brain.

In taking fish audiograms, some researchers use no anaesthetic and others use a range of different anaesthetics (e.g., Fentanyl and MS-222), which may differ in the impact each has on the brain activity of the fish[77].

Maruska and Sisneros[78] recently commented on the lack of a universal mapping factor between behavioral auditory thresholds and thresholds for fish determined by AEPs, and this is further explored in Section 8.

What must be factored into experiments or interpretations that compare different measurement methods for thresholds, is whether or not they correctly recognize that the thresholds themselves are different when drawing conclusions (Section 8), and to what extent any variation is due to the differences between the measurement methods used (discussed here), or the differences between individual fish tested. This issue leads on to the topic of the next section.

Takeaway: As with section 3, the question here is perhaps not to what extent are today's procedures and equipment adequate, but rather to what extent must we re-evaluate the wisdom and literature that today's researchers inherit based on the calibrations and procedures and complexities present when aquatic acoustics started. It should be of concern that we build up our picture of a field using publications that rely on data taken from instruments with performance acceptance limits of $-\infty$ dB; that we must question what the literature has always meant by 'normal hearing' (Figure 5); and that existing guidelines for high frequency measurements contain ambiguities making some exposures acceptable when read one way, and unacceptable when construed using an equally valid interpretation.[25] Lack of standardization is always a concern,[69] yet once something is codified into a standard, errors in it become extremely difficult to correct even if they lead to frequent mis-diagnosis.[67]

5. RELIANCE ON THE CONCEPT OF A 'TYPICAL' SUBJECT BASED ON AN AVERAGE

If we need a hearing aid, we expect it to be based upon our personal audiogram. However, if we visit a noisy factory (which will usually not have access to the personal audiograms of visitors), we can expect our hearing to be protected by regulations that, rather than being based on the susceptibility of the 'average' human, instead take into account that a visitor might be particularly susceptible[79] (with local variations based on national guidelines; Section 2).

As we move out of the frequency range covered by standard audiological testing, to the frequencies higher than 8 kHz (but which we still expect to be audible to a healthy young adult), Figure 5 indicates the possibility of very significant subject-to-subject variability. Even if an audiogram has been taken for an individual (human or fish), without a reliable 'mapping' between it and some other (e.g., adverse) response (absence of which Maruska and Sisneros[78] note; see Sections 4 and 8), that audiogram cannot be used to predict thresholds for that other response; and given inter-subject variabilities, even with such a mapping, the audiogram cannot reliably be used to predict the behavioral threshold of another individual of the same species beyond a probabilistic prediction that would be accurate only over a large number of tests.

How therefore can we make predictions of the behavioral response of an individual for whom we do not have individual hearing threshold data, using just our knowledge of the thresholds of the population of individuals measured to date? When it comes to humans exposed to airborne-VHF/US, or a researcher exposing fish to lower frequencies, how can a researcher know how many subjects to use in the experiment, if they do not know the degree to which there is subject-to-subject variation in responses in nominally identical individuals? A standard power analysis to assess the possibility of detecting an effect may give a false sense of security if the current cohort and literature fail to cover rare sensitivities. This will not matter if the object is to protect a population, but will matter if the law requires that all individuals be protected (Section 2).

For airborne-VHF/US, we are only just discovering the extent to which the response between individuals varies. The evidence of Figure 6a suggests that 5% of the people tested by Rodríguez Valiente *et al.*[80] who were between the ages of 40 and 49 years old, had hearing at 20 kHz that was at least 20 dB more sensitive than the median for the 30–39 year olds tested. At 20 kHz, 5% of the 5–19 year age group had a threshold 60 dB more sensitive than the median for the 30–39 year age group.

Such vast variation between individuals undermines our ability, when confronted with an individual, to compare them to some 'norm' meaningfully. Figure 6b shows that this inter-subject variability is not only confined to the 20 kHz TOB, but also the one centered on 16 kHz. This has practical implications. When using high frequency audiometers, the protocol is to report dB HL (Hearing Level) as was done in Figure 5. The dB HL is the dB difference between the dB SPL of the quietest signal that a given subject can hear, compared to average hearing threshold in dB SPL for the average, normal-hearing listener. However in the original paper on which these norms are based, the author, Frank[81] stated that '*Normative high-frequency thresholds could not be recommended for clinical use due to the very large inter-subject threshold variability. This occurred even though test versus re-test thresholds were not significantly different (p > 0.05) at any frequency…Future research should concern intrasubject threshold reliability and variability rather than specifying inter-subject normative thresholds*'. Frank[81] based this 1990 warning on test/re-test data exposing (to pure tones at 10, 12, 14, 16, 18, and 20 kHz) a total of 200 ears of 100 young adults (aged 18-28 years old) who had all been judged to have normal hearing using standard audiometric testing (covering the third octave bands centered on 0.25 to 8 kHz).

Takeaway: We have hearing threshold data on a significant number of the humans who have lived in the last 50 years, including longitudinal studies of individuals, and correlation with their history of exposure to noise, chemicals etc. That, for just one species, is inadequate to predict any response (sensitivity, adverse effects, etc.) of an individual on whom we have no data using just measurements of the population, except at the extremes (extremely low/high amplitudes, or extremely low/high frequencies). This lends perspective to the problem facing those who study the acoustic responses of fish. Over 33,000 living species of fish have been reported worldwide[82,83].

Research groups commonly use a limited number of model species to investigate questions on fish hearing (commonly because said species is easy to acquire, or is already known from the literature to respond to sound – e.g., goldfish). This approach is useful for understanding some fundamental questions, but a large gap in knowledge exists for other species. Although physiological similarities exist between species belonging to a family, evolutionary differences and adaptations of individual species have the potential to be enormous (e.g., silver carp *Hypophthalmichthys molitrix* have hearing thresholds with higher SPLs than either common carp *Cyprinus carpio* or goldfish[74]). This leads onto the topic of the next section, the reliance on data from too few subjects.

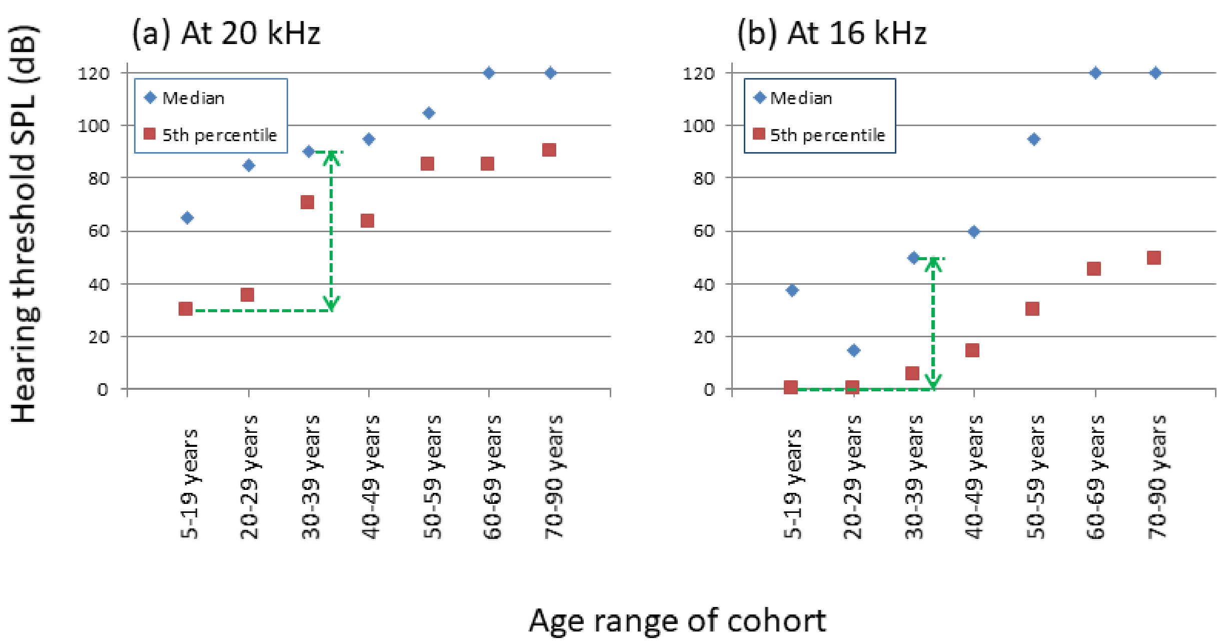

***Figure 6.** (color online) The hearing threshold (pure tone audiometry) as a function of age, showing median and 5th percentile values at (a) 20 kHz and (b) 16 kHz. Figure taken from Leighton[1] plotting data from Rodriguez Valiente et al.[80], who used a total dataset of 645 people. Data at 0 dB and 120 dB re 20 μPa have been influenced by the threshold and saturation limits of the instrumentation and so contribute less reliably to the statistics. The vertical arrows indicate the difference between the median in the 30–39 age group, and the 5th percentile in the 5–19 age group.*

6. RELIANCE ON DATA FROM TOO FEW SUBJECTS

The work of Knight[84] on the response of humans to VHF/US is frequently cited, drawing upon his conclusion that '*there is no evidence of hazardous influence of airborne ultrasonic radiation on the acoustic or vestibular systems*'.[84] To counter the widespread quotation of this assertion, Leighton[1] asked, specifically, 'What question was Knight[84] really asking?', and answered[1] it in the following manner: '*If a group of only 18 men with an average age of 30, who work in the ultrasonic cleaning baths industry but for whom there is no quantification of exposure either to audio frequency or ultrasonic signals, is compared to a group of 20 men of similar average age who do not work in the ultrasonic cleaning bath industry, do the average (across the whole group) Hearing Threshold Levels from 250 to 8000 Hz differ between the two groups?*'. The average of the ultrasonic workers was worse by 2–7 dB over the entire frequency range. However, Knight's data also show the most pronounced reduction as being a dip at 4 kHz, which usually follows from exposure to high levels of audio frequency sound. Indeed, Knight[84] records that half of the 18-man cohort had experienced gunfire, of which one was also working with pneumatic road drills, one with riveting noise and one (who had also received an ototoxic drug) had worked in an aero-engine test bed. Of the remaining nine men who had not experienced gunfire, two tested 100 W guitar amplifiers between their ultrasonic exposures. This would negate comparisons. In common with many studies that looked for changes to hearing associated with ultrasonic exposure, Knight[84] adds as a postscript that '*The reported prevalence of subjective effects and stress disorders was extremely small*'. That is to say, adverse effects from ultrasound that are generally termed subjective (nausea, dizziness, migraine, fatigue, tinnitus and 'pressure in the ears'[1, 85-89]) were dismissed as less significant to the study, yet it is these that are probably of more interest given current levels of public exposure to VHF/US. It is also these subjective effects, rather than hearing threshold shifts, that one would seek to generate in fish to evoke an immediate behavioral response when discussing, for example, the use of sound as a fish deterrent. These subjective effects are also the ones of interest when estimating the impact on fish feeding, migrations and social behavior etc. of sound that may not be loud enough to cause threshold shifts.

In the context of how many subjects one should test, and what one should measure (behavioral effects or AEPs) given the purpose for which the data is to be used, Knight's cohort lacked gender- and age-diversity that might make one question whether they reflect the population of interest (if, for example, one were setting MPLs for VHF/US emitters to avoid 'failure to concentrate' in a mixed-gender pre-school classroom). When VHF/US device-development companies use their own employees to test for adverse effects of VHF/US, they may be selecting out those who, having experienced ill effects from VHF/US, would not start, or continue, to work with the company[90].

There are immediate parallels in the selection of cohorts and test criteria for fish. Moreover, what we know of the histories of Knight's cohort might raise questions as to whether their life experiences might have compromised their suitability to provide data giving us predictive capabilities for those without previous exposures known to be damaging to hearing (notably, for the hypothetical pre-schoolers mentioned above). So too with fish, particularly wild fish: The experimenter is unlikely to be aware of prior acoustic exposure, and indeed of the overall health of an individual (e.g., parasites), its exact age and exposure to other detrimental pollutants, etc. This does not necessarily make the fish raised in captivity the ideal subject if one is to design a deterrent for use on wild fish. Fish sourced from the wild tend to provide an increased applicability of results, as they are a product of the environment they have developed in and are adapted to (e.g., in terms of predator avoidance, seasonal changes, additional stimuli etc.). Hatchery-bred fish, on the one hand, are often morphologically different[91] to their wild counterparts, and will often display behavior[92] that differs from wild individuals. On the other hand, hatchery-sourced, or artificially-reared, fish are more likely to have a known or traceable life-history (e.g., genetic strain, exact age, history of disease/ infection, etc.). As introduced in Section 4, hatchery-raised fish may differ from wild fish in terms of lifetime prior noise exposure. However, in the absence of standards there might be no records of this, both to control that variable, and assess to what extent it resembled the experience of the wild fish to which one wishes to apply the laboratory results (noting that, just as noise exposure history might vary between hatcheries, so too will it vary between geographical locales for wild fish of the same species). We are clearly a long way from controlling the lifetime history of test fish to ensure the data we gather from them is fully representative of those in the field at the location of a proposed noise deterrent. In contrast, no rigorous hearing experiment on humans would be undertaken without a good history for each individual subject.

Table 2. Example studies highlighting maximum replicates (n) per investigative parameter of fish undergoing AEP (◊) and/ or behavioral (*) testing when studying hearing sensitivities. The definition of the IUCN Classification Abbreviations is as follows: CE = Critically Endangered; Vu = Vulnerable; NT = Near Threatened; LC = Least Concern; NE = Not Evaluated. It is important to note that IUCN considers worldwide status without provisioning consideration for localised conservation status or ecological importance of a species.

Study refs.	**Subject species**	***n***	**IUCN Classif-ication**	**Commercial importance**	**Geographic origin**	**Source**	**Complimen-tary tests**
Casper *et al.*, (2003)[93]	Little skate ◊ (*Leucoraja erinacea*)	4	NT	na	Marine Resources Center, Woods Hole, Massachusetts, USA	Laboratory	Behavioural conditioning tests *
Kastelein *et al.*, (2017)[94]	European seabass * (*Dicentrarchus labrax*)	9	LC	Commercial fishing	Ecloserie Marine, Gravelines, FRA	Hatchery	Comparison between small and large individuals
Kenyon *et al*, (1998)[95]	Goldfish ◊ (*Carassius auratus*)	8	LC	Aquarium trade	Unknown (Study conducted in USA)	Aquarium	Compared to behavioural studies (Jacobs and Tavolga, (1967)[96]; Popper, (1971)[97]
	Oscar ◊ (*Astronotus ocellatus)*	8	NE	Aquarium trade/commercial fishing			
Lovell *et al.*, (2006)[98]	Silver Carp ◊ (*Hypopthalmichthys molitrix*)	12	NT	Commercial & recreational fishing	Unknown (Study conducted in USA)	Unknown	
	Bighead carp ◊ (*Aristichthys nobilis*)	12	NE	Commercial & recreational fishing			
Mann *et al.*, (2007)[72]	Lake chub ◊ (*Couesius plumbeus*)	5	LC	Bait fishing/aquarium trade	East Channel of the Mackenzie River, Inuvik, NWT, CAN	Wild	
	Longnose sucker ◊ (*Catostomus catostomus*)	4	LC	Recreational fishing			
	Trout-perch ◊ (*Percopsis omiscomaycus*)	4	LC	Bait fishing/ aquarium trade			
	Nine-spined stickleback ◊ (*Pungitius pungitius*)	4	LC	Aquarium trade/ artisanal fishing			

	Northern pike ◊ (*Esox Lucius*)	5	LC	Commercial & recreational fishing			
	Spoonhead sculpin ◊ (*Cottus ricei*)	4	LC	na			
	Burbot ◊ (*Lota lota*)	1	LC	Commercial & recreational fishing			
	Broad whitefish ◊ (*Coregonus nasus*)	5	LC	Commercial & recreational fishing			
Lechner *et al*, (2010)[99]	Squeaker catfish ◊ (*Synodontis schoutedeni)*	12	LC	na	Malebo Pool[a], Congo River, COD, and Transfish[b], Munich, DEU	Wild[a] and aquarium[b]	Comparison of ontogenetic developmental stages
Yan and Popper, (1991)[100]	Goldfish * (*Carassius auratus*)	2	LC	Aquarium trade	Unknown (Study conducted in USA)	Aquarium	
Popper, (1972)[101]	Goldfish * (*Carassius auratus*)	4	LC	Aquarium trade	Unknown (Study conducted in USA)	Unknown	

Table 3. Example studies highlighting maximum replicates (n) per investigative parameter of individuals undergoing AEP testing when examining auditory threshold shifts of fishes exposed to noise.

Study refs.	**Subject species**	***n***	**IUCN classifi-cation**	**Commercial importance**	**Geographic origin**	**Source**	**Compli-mentary tests**
Amoser and Ladich, (2003)[102]	Goldfish (*Carassius auratus*)	6	LC	Aquarium trade	Unknown (Study conducted in *AUT*)	Aquarium	
	Pictus catfish (*Pimelodus pictus*)	6	NE	Aquarium trade			
Caiger *et al.*, (2012)[103]	Australasian snapper (*Pagrus auratus*)	19	LC	Commercial & recreational fishing	Kaipara Harbour[a] & Plant and Food Research, Nelson[b], *NZL*	Wild[a] & hatchery[b]	
Codarin *et al.*, (2009)[104]	Brown meagre (*Sciaena umbra*)	6	NT	Commercial & recreational fishing	Trieste Gulf, North Adriatic Sea, *ITA*	Wild	

	Mediterranean damselfish (*Chromis chromis*)	6	LC	Recreational / bait fishing (minor commercial)			
	Red-mouthed goby (*Gobius cruentatus*)	6	LC	Aquarium trade			
Crovo *et al*., (2015)[105]	Blacktail shiner (*Cyprinella venusta*)	5	LC	Bait fishing/ live aquaria feed/ aquarium trade	Little Uchee Creek, Lee County, Alabama, *USA*	Wild	Elevated cortisol levels
Gutsher *et al*., (2011)[106]	Goldfish (*Carassius auratus*)	6	LC	Aquarium trade	Vienna, *AUT*	Aquarium (pond)	
Halvorsen *et al*., (2012)[107]	Channel catfish (*Ictalurus punctatus*)	9	LC	Recreational fishing & aquaculture	Fish Haven Farm & Fingerlakes Fish Farm, NY, *USA*	Hatchery	
	Rainbow trout (*Oncorhynchus mykiss*)	9	NE	Commercial & recreational fishing			
Ladich and Schulz-Mirbach, (2013)[108]	Orange chromide (*Etroplus maculatus*)	6	LC	Aquarium trade	Unknown (Study conducted in *AUT*)	Aquarium	
	Slender lionhead cichlid (*Steatocranus tinanti*)	4	LC	Aquarium trade			
Liu *et al*., (2013)[109]	Chinese sucker (*Myxocyprinus asiaticus*)	5	NE	Aquarium trade	Taihu Jingzhou, Yangtze River Fisheries Research Institute, *CHN*	Hatchery	
Popper *et al*., (2005)[110]	Broad whitefish (*Coregonus nasus*)	7	LC	Commercial & recreational fishing	Mackenzie River Delta, Inuvik, Northwest Territories, *CAN*	Wild	Follow up study on inner ear tissue damage (Song *et al*., (2008)[111])
	Lake chub (*Couesius plumbeus*)	7	LC	Bait fishing/ aquarium trade			
	Northern pike (*Esox lucius*)	7	LC	Recreational fishing			
Scholik and Yan, (2001)[112]	Fathead minnow	6	LC	Bait fishing/ live aquaria feed/	Frankfort State Hatchery,	Hatchery	

	(*Pimephales promelas*)			aquarium trade	Kentucky, *USA*		
Scholik and Yan, (2002)[113]	Bluegill sunfish (*Lepomis macrochirus*)	6	LC	Recreational fishing	Newtown, Ohio, *USA*	Hatchery	
Smith *et al*., (2006)[114]	Goldfish (*Carassius auratus*)	6	LC	Aquarium trade	Unknown (Study conducted in *Maryland, USA*)	Hatchery	Hair cell bundle loss
Vasconcelos *et al.*, (2007)[115]	Lusitanian toadfish (*Halobatrachus didactylus*)	9	LC	Artisanal fishing/ fishmeal/ oil production	Tagus and Mira Rivers, *POR*	Wild	

Table 2 considers papers solely looking at hearing sensitivities of fish. Table 3 summarizes papers which examined auditory threshold shifts in fish hearing under noise conditions. The dataset is clearly much less than that for humans measured to frequencies up to and including 8 kHz (actual, not TOB), though probably greater than the controlled laboratory tests of human exposure to ultrasound. Few would suggest that the behavior of an untested individual fish in response to an acoustic stimulus could be predicted from Table 2 (let alone its behavior in a group). Table 3 can be interpreted as indicating an adverse effect (a threshold shift) which we would wish to avoid inducing (either temporarily or permanently), but even if (as with fish) we only want to protect most of the population (as opposed to all the population, in humans), nevertheless it is important to know the inter-subject variability in threshold tests.

Furthermore, the choice of frequency of interest (e.g., for adverse effects on behavior, health, social interactions, feeding etc.) is almost always determined from audiograms measured on a sample of other fish of the same or a similar species (Section 8). If this were to lead to the implicit assumption that a sound which the fish cannot hear cannot affect it, then the work on the adverse effects of airborne-VHF/US on humans (who can report to experimenters such concepts as feeling an 'unpleasant feeling of pressure in the ears') should make us question that assumption, particularly given inter-subject variability (Sections 5 and 6) and the possibility that the conditions under which that audiogram was taken (with or without anaesthetic, hatchery- or wild-raised fish etc.) might introduce an unrecognized variable. One such is also the possibility of group effects: if for example the fish is always going to be in a group when it meets a deterrent, the use of data taken when a member of the species was in isolation must be of course questioned, a topic for the next section.

Takeaway: We rarely know the history of exposure of aquatic life, but would not undertake human experimentation without a complete history that might also include questions about recent rest and stimuli (e.g., caffeine).

7. INSUFFICIENT APPRECIATION OF GROUP EFFECTS

The authors know of no studies on how the application of airborne-VHF/US to a group, as opposed to individuals, alters the response of the humans involved. Section 10 identifies a point of overlap, following the suggestion that, given how unlikely[9] it was the ultrasonic weapons were used against US Embassy staff in Cuba and China, it is possible that a group psychogenic illness was responsible for the phenomenon[116,117].

Displays of collective group behavior are common across differing animal taxa, including fishes (e.g., schooling or shoaling behavior[118]). Anthropogenic noise can impact the behavior, anatomy or physiology of an individual fish. However, our understanding of how noise impacts collective behavior, such as shoaling or schooling, is lacking[119-122].

Group behavior is an exceptionally important strategy employed by a number of fish species, as it facilitates a variety of survival functions, including social information exchange, and anti-predator defence. While a school may appear to act as a single collective entity, it is in fact made up of a group of individuals working within that collective, dependent on a complex feedback matrix through interactions with other individuals and the surrounding environment[123].

AEP hearing thresholds are not designed to incorporate information transfer among individuals within a group who will vary in auditory sensitivities, and internal cognitive processes (such as motivation to respond), and who might be influenced by complex social cues.

Takeaway: When we test the responses of individual fish, it is a mistake to allow the contribution to our knowledge base from data on the most sensitive individuals to be lost by their dismissal as outliers, or lost through subsummation of their data into an average that they fail to influence significantly, if (as can occur in fish, humans and other species) the most sensitive individual in a population can influence the group response (e.g., a startle response).

8. RELIANCE ON A TACIT ASSUMPTION OF A RELIABLE MAPPING BETWEEN THRESHOLD FOR HEARING AND THRESHOLD FOR BEHAVIORAL/ADVERSE EFFECTS

Established practices, introduced for pragmatic reasons in the early days of researching a given field, can be detrimental in later years because of the propensity of the scientific community to suspend its normal skepticism in the face of received wisdom from other more established researchers. For the study of airborne-VHF/US, these include:

- The acceptance that humans cannot hear above 20 kHz, because the lower limit for ultrasound is 20 kHz and humans cannot hear ultrasound. The first of these statements is incorrect (some humans can hear above 20 kHz), and the second contains a logical disconnect (which carries over, for example, into a disconnect[8] between the remits of bodies setting guidelines, and the frequencies for which they set guidelines). This pair of influential statements have been unchallenged for decades, which has led to the introduction of VHF/US technology without consideration for adverse effects. With limited time and resources, there is an imperative not to explore the response outside of the commonly-accepted frequency band, often as assessed by AEPs or behavioral audiograms. Vetter *et al.* observed the behavior of bighead carp (*Hypophthalmichthys nobilis*)[56] and silver carp[124] to acoustic stimuli above 500 Hz, sensibly conserving their resources because the audiograms of both species suggest they are insensitive below 500 Hz. However, if no researchers explore these possibly fruitless regimes then certain effects (e.g., sensitivity to particle velocity at low frequencies) might remain undiscovered.
- The preponderance of tests looking for adverse effects in humans to study for temporary or permanent shifts in hearing threshold, such that any other effects (e.g., ear-ache, headache, excessive fatigue, irritability, nausea, feelings of fear, feelings of pressure in the ear, failure to concentrate, discomfort and annoyance) have been ignored or mentioned only as an afterthought (see Section 6). MPLs above 22.4 kHz are based on hearing threshold shifts, whereas MPLs below 17.8 kHz are based on the so-called subjective effects (with a mix in the 20 kHz TOB)[1]. Data on actual adverse effects in humans is rare,[21,22,125,126] especially in controlled experiments and especially on children, because of ethical bars. An assumed mapping must be used, in a conservative way, to protect the public. The only mapping used to date[29] for public protection was a first-guess, and was labeled as 'interim' in 1984 and has not been revisited.

In both of the above bullet points, there is an implicit assumption that the audiograms were taken with sufficient population sizes, and the inter-subject variability is sufficiently small, to ensure the validity of their application for prediction or protection. We have seen that this is probably not the case for public exposure to VHF/US. The issues raised in the preceding sections should prompt discussion of whether the published record of audiograms is sufficient to provide the aforementioned validity, e.g., whether there is sufficient sampling of members of the fish population, whether the audiograms are representative (Sections 5 and 6), and whether there is a reliable mapping from the phenomena measured in taking those audiograms, to the route by which protection in the field will be implemented. When considering adverse effects of ultrasound on humans, there is wide use of an unstated assumption that there exists a consistent and reliable mapping between the threshold of hearing and the threshold for adverse effects. This has not been proven, and might be thought unlikely given the range of adverse effects, and the inter-subject variability. Scholkmann[12] notes that Kühler *et al*.[127] report that *'almost all of the test subjects described the hearing sensation as displeasing'* and they confirmed the prediction[8] that *'close to the high frequency limit of an individual's hearing, the dynamic range between being able to hear a sound and finding it unpleasant is very small*'.

The development of acoustic deterrent systems frequently rely on our understanding of hearing thresholds, acoustic masking, signal to noise ratio and the critical bands of fish. These metrics are commonly obtained through experiments investigating auditory sensitivity via AEP techniques including the auditory brainstem response (ABR), which is an early latency evoked response[128-130]). The capability to detect an acoustic stimulus above a sensitivity threshold, does not necessarily signify that a desirable change in behavior will be observed (e.g., a "C-start" escape response)[131]. Other internal (e.g., non-locomotor) processes[131] may determine the responsiveness of an individual fish to a particular stimulus (e.g., motivation to escape); or more subtle, or less extreme changes in behavior may be occurring (e.g., slight motion of the pectoral or ventral fins).

In Section 4 in the context of the need for standardized methods, mention was made of the recent white paper by Maruska and Sisneros[78], who noted that '*there is no universal conversion between behavioral auditory thresholds and AEP-determined thresholds*', noting that '*Auditory thresholds varied by as much as 10–25 dB among [electrophysical] techniques [in the Hawaiian sergeant fish and in the Lusitanian toadfish]*' and that '*thresholds at best frequency [for Hawaiian sergeant fish were] determined via single cell recordings were ~15–25 dB lower than those measured by AEP and saccular potential techniques*'.

Such studies[74,78,] indicate a need for caution when comparing hearing threshold measured by different techniques, and even when the same technique is used but with different methodologies. However, once methodologies have been standardized, we should not expect exact agreement between hearing thresholds measured by electrophysiological and behavioral methods. Logic might lead one to expect that the threshold for AEPs may or may not be consciously registered by the subject, and certainly need not be a cause for a behavioral response in a fish if the level and character of the noise does not warrant it (unnecessary behavioral response wastes energy, can interrupt core activities, and can upset social interactions).

Takeaway: The mappings discussed here do not currently exist for any species, and we should therefore recognize this on those occasions when we are forced to assume one.

9. UNDERSTANDING THE COMPLEMENTARY BENEFITS OF FIELD AND LABORATORY OBSERVATIONS

We live in an age where, by purchasing a $50 garden pest deterrent, one can inadvertently expose neighboring children to levels of airborne-VHF/US exceeding MPLs, levels set based on exposure of adults who are likely to be less prone to adverse effects. Section 1 illustrated some of the SPLs generated at the position the human can occupy, from commercially-available devices (e.g., 120 dB re 20 µPa SPL at ~20 kHz right under the device at a 1.6 m, and 90 dB re 20 µPa SPL at 14 m range) and devices in development (155 dB re 20 µPa in the 40 kHz TOB from the proposed use of haptic feedback; Figure 2). However whilst these levels exceed the MPLs for public exposure (of 70 dB re 20 µPa SPL below 22.4 kHz and 100 dB re 20 µPa above it)[29], our controlled laboratory tests of human volunteers must be informed by those guidelines, exceeding them only because the duration of exposure could be kept very short[125,126]. With such limited exposures, lower than occur every day to members of the public, our UK laboratory could measure adverse effects[125] on adults in controlled laboratory conditions for ultrasonic signals they could hear; but the data[126] at higher frequencies (which they could not hear) showed no adverse effects for the short, relatively low amplitude exposures that were permissible within the ethical guidelines. These levels fell short of the longer, higher amplitude exposures they would receive in the field; indeed, such ethical consideration means that the study runs the risk of being taken out of context to state that people cannot suffer adverse effects from sounds too high to hear. In such circumstances in the UK, the field offers the only option for finding out if humans suffer adverse effects from sounds pitched too high for them to hear. This is an important consideration in a country where devices emitting signals on the border between sonic and ultrasonic are sold as teenager deterrents, for example to shift the demographics of shoppers towards an older clientele, to the extent that the UK government is considering licensing[7,132] their use to restrict them only to areas where people have no right to be (such as railway tracks). Without field observations, it is difficult to imagine such a rapid translation of research to Government action. Other laboratories, notably those in other countries[20], may have the opportunity to test the response of humans in controlled laboratory conditions with exposures to higher amplitudes and longer durations, and have also obtained valuable feedback from field trials[21,22].

However, field measurements come with their own drawbacks. There are few opportunities to map the acoustic field without spatially under-sampling (Section 4) and measuring where the presence of the subjects might distort it (Section 3). Indeed, when the VHF/US output of PAVA systems was first discovered[1], the amplitude measured in the field was higher than in subsequent measurements at other sites[23,24], and subsequent enquiries suggest that this is because the first field measurement site contained many dozens of large speakers (and pest scarers) in an enclosed reverberant space: this is not the laboratory measurement of a single device, but does represent the field to which the public are exposed daily. Whilst in field trials one seldom has the opportunity to take the histories one would like (e.g., conduct hearing tests of the subjects or note, through questionnaire, their medical history and previous noise exposure prior to the VHF/US exposure), or to recruit enough subjects (Section 6), nevertheless the data can be more effective at influencing owners of establishments that deploy the devices, and in the end, policymakers.

This has parallels to research on the exposure of aquatic life to sound. The ability in tanks to map out the field and even measure if the presence of the fish changes it, to control the background noise and the numbers of subjects to achieve statistical significance, are major advantages. Although, as noted in Section 4, there are no MPLs for the levels to which fish might be exposed either during tests or in hatcheries prior to such tests, the closeness of field experiments to the end-user scenario has benefits in outreach to public, facility owners and policymakers.

Currently, it is not uncommon to hear fish bioacousticians expressing concern that there are problems in carrying out acoustic experiments in tanks, because of the extent to which conditions differ from those that would exist in the natural environment. However, the issue is sometimes not the extent to which laboratories differ from *natural* environments, but rather the extent to which they differ from the *field* environments, and for the location of acoustic deterrents and loud anthropogenic sounds these field environments can include manmade channels (Figure 3).

Whilst a shallow tank with hard, flat man-made walls and the proximity of the pressure-release surface at the top of the water column is a poor mimic for the environment of deep-water fish, it might well mimic the infrastructure where there is concern that industrial noise could adversely affect a migrating population, or where we wish to design acoustic deterrents to steer fish away from industrial water extraction points, or to support the use of physical screens (which can be ineffective for weak-swimming fish of low cross-section, such as juvenile eels[133-135]). This is particularly important for species that migrate through fresh water, where the confinement of shallow waters in rectangular geometries and man-made walls of the laboratory environment can resemble regions through which fish pass, and where anthropogenic noise and the need for acoustic deterrents might be particularly high (Section 3; Figure 3).

The presence of some field environments that resemble tanks (with their small sizes, the large impedance and elasticity of walls and support structures) should not mask the mismatch between tanks and most open-water environments[136, 137,] particularly for deep-water species away from the water/atmosphere interface, especially when using tank dimensions much smaller than the acoustic wavelength of the frequencies of interest[138]. It is important to understand these limitations, and intricately map the acoustic environment a fish is exposed to under laboratory-based studies. This way, researchers can assign behavioral response to be solely based on the external stimuli to which an individual is exposed (alongside a range of internal cognitive processes), without the influence of additional confounding variables, which can be found under field settings.

In summary, laboratory studies are commonly deployed and accepted as a valid methodological approach in the study of the effects on organisms of aquatic noise and Airborne-VHF/US, the inclusion of artificial environments being an important step to limit the influences of secondary stimuli, or observer-influence effects. However it is vital to characterize these artificial environments, so that complementary studies[139,140] can be conducted.

Takeaway: The takeaway is not that tank conditions differ from field conditions: this is self-evident and has been extensively written about. The takeaway is rather that one should beware an underlying assumption that data from tank experiments are necessarily less representative; and beware a confusion that replaces ‘field conditions’ with ‘natural conditions’: tanks and flumes are clearly not natural, but at locations critical to their being caught (deliberately or inadvertently) or affected by anthropogenic sound, fish ‘in the field’ have been passing through man-made infrastructure for over 2000 years.

Figure 7. (color online) Pairs of pages from 1947-1948 magazines (a,b) Popular Mechanics Magazine[141] and (c,d) Flying[142] (red squares added to highlight relevant text).

10. CONFUSION CAUSED BY INEXPERT REPORTING

Since the first reports publicizing 'ultrasonic sickness' in the 1940s, misinterpretation and possibly misrepresentation of the facts by the media and influence-generators has created a fog of concern or dismissal that smothers the few rigorous scientific findings. The cautious statements by scientists, correctly staying within the limits of what they know, come across to the public as less clear than direct statements by politicians and headlines by newspapers. Because human trials, for a sensitivity that displays such huge inter-subject variation, requires large numbers of exposures to generate reliable statistics, and because the use of high 'doses' to produce clearer results is ethically challenging when the researcher is trying only to stimulate adverse effects (to which children might be most sensitive), often the statistics fail to show an effect, which can be misunderstood as statistically failing to show an effect. This is particularly the case when general conclusions (e.g., applying to future field exposures) are drawn from specific experimental protocols and conditions. Two recent studies illustrate the danger of such misinterpretations in studies exposing humans to ultrasound, both of which showed no response, but should not be taken to prove that there can be no response in the field. In one case[126] the amplitudes and durations that were allowed in the test were limited by the Ethical Approval to levels well below many field exposures. In the other case[127] the baseline stimulation to attempt to detect brain activity in response to acoustic exposure, was a 14 kHz tone that was 20 dB above the individual's hearing threshold at that frequency; however that individual was then exposed to ultrasound at no louder than 5 dB above that individual's hearing threshold for the ultrasonic frequency, raising the detectability threshold for any ultrasonically-induced effect.

The year of 1948 saw the first legal case for injury by ultrasound, by which time magazine articles were discussing ultrasonic sickness and death rays: Figure 7(a,b) has *Popular Mechanics Magazine*[141] in 1947 quoting a man with a prototype ultrasonic dental drill telling readers that 'it would be easy to design an ultrasonic "death ray" gun that would kill a rabbit or dog at 60 feet'; whilst a 1948 issue of *Flying Magazine*[142] reports that the US Navy has completed tests on human subjects and concluded that 'ultrasonic noises from jet engines are harmless to humans, despite wild rumors to the contrary' having exposed Navy men (protected by a helmet or springband headphones, double kapok-filled "ear doughnut" and cotton earplugs) and finding that 'some of the men lost weight and seven said they were more tired than ordinarily', suggesting that other reports of sickness induced by ultrasound 'may be pure sensationalism, or caused by "suggestability" '. In 1966 Parrack wrote: 'Ultrasonic sickness, as described around 1948–1952, appears to be largely of psychosomatic origin and engendered by the apprehension and/or fear growing out of speculative publicity about the effects of air-borne ultrasound'[143] and one year later this quote (which owed its genesis to the exposure of jet engine workers to a great deal of audio- frequency noise and possibly some ultrasonic energy) was used by a representative of the cleaning bath industry[144] to argue that no hearing protection needed to be used by long-term operators of ultrasonic baths in hospitals (a completely different qualitative exposure, let alone the difference in frequencies, durations and levels).

This unsatisfactory drawing of conclusions based on inadequate data continues to this day. In August 2017 the Associated Press (AP) [145,146] was the first to report claims that, in the US Embassy in Cuba: '*the diplomats had been exposed to an advanced device that operated outside the range of audible sound and had been deployed either inside or outside their residence*'. By December 2017, the Associated Press reported that '*Doctors treating the U.S. embassy victims of suspected attacks in Cuba have discovered brain abnormalities*'[147]. The first reports of 'white matter tract' changes surfaced. The 'sonic attacks' were given significantly more political weight when Senator Marco Rubio stated that '*It's a documented FACT [sic] that 24 U.S. govt officials & spouses were victims of some sort of sophisticated attack while stationed in Havana*', as reported by the Miami Herald[148] on 7 January 2018. The following day CBS Miami[149] reported that Rubio was going to set up Senate Hearings entitled 'Attacks on U.S. Diplomats in Cuba: Response and Oversight', and that these 'attacks' had caused: '*changes to the white matter tracts that allow different parts of the brain to communicate. Victims have reported damage to their hearing, vision, balance and memory. Meantime Secretary of State Rex Tillerson, while in Belgium, said he is convinced the incidents were targeted attacks*'.[149] The day after that, Rubio speculated on the reasons behind the 'attack'[150].

However these claims of brain damage, propagated rapidly by the media and politicians, did not appear to be borne out in the limited results that were published (Swanson *et al.*[151] published no raw data for other investigators to check). With regards to the white matter changes reported, the authors found 3 of the 21 patients tests had '*more than expected for age, 2 mild in degree, and 1 with moderate changes…the findings could perhaps be attributed to other preexisting disease processes or risk factors'* (the word 'other' meaning not associated with an attack on the Embassy). The brain injury tests[151] were criticized[9,117] for elements outside of their control (lack of etiology, no possibility of a control group or calibrated acoustical field measurements of the type required to determine adverse reactions, no reactions, and nocebo effects). They were also criticized[9,117] for supplying only percentiles and not the raw data, and providing no demographic data (although this may have been out of the control of the researchers given that Rubio had opened hearings[9] on the purported 'attack'). However, brain injury test methodology[151] was also criticized[9,117] for choices that surely were in their control, such as use of only a psychometric approach; and, as Della Sala and Cubelli make clear[117], of selecting performance below the 40th percentile as the threshold for an 'abnormal' result, so high as to give numerous false positives (a criterion where 5% of the normal population would be expected to 'fail' the test is more usual). This latter choice is crucial because politicians and the media repeatedly used wording that would leave the listener/reader with the impression that all of those attacked were confirmed as injured. For example Rubio stated, in opening his hearings[152], that: '*While the symptoms may vary, <u>all</u> of the medically-confirmed cases, <u>all</u> 24 of them, have described some combination of the following symptoms: sharp ear pain, dull headaches, ringing in one ear, vertigo, visual focusing issues, disorientation, nausea and extreme fatigue, <u>facts</u> that will be testified to today by our panel*'. The casual listener might forget that these 24 were downselected from an initial 80 complainants (plus others - the number of which has never been published – who were examined to see if they also show the set of symptoms that were being looked for), and then the data of all but 24 were discarded to leave a group with one or more of a selection of 8 symptoms (several of which are common and can be attributed to a variety of causes). Returning to the choice of the 40th percentile, for example in tests of damage to executive function (the processes, controlled by the frontal lobe of the brain, that allow an individual to manage themselves and their resources, including for example working memory, self-control, flexibility in thinking, planning, paying attention etc.), that choice would give a normal individual, who had never been exposed to an attack, a 95.3% chance[9] of failing the test and being labeled as having damage to the executive function of the brain. Meanwhile, whilst the similarity of the selection of 8 symptoms to those listed for 'ultrasonic sickness' was raised by many, few presented the balancing arguments, that these medical tests were conducted on average 203 days (range, 3-331 days; median, 189 days; interquartile range, 125 days) after the suspected exposure, whereas published reports of adverse effects from ultrasonic exposure showed them disappearing after exposure ceased. Furthermore, whilst a device such as a pest scarer could ensonify a room, it would be an unlikely weapon to choose against middle-aged men if it were the case that their loss in high frequency hearing sensitivity could be mapped to a robustness against ultrasonic adverse effects (what else does a weapons designer have to go on in the published literature?); and claims that an ultrasonic beam could have been fired from across the street, through walls, ignored the absorption of air and solids, and the reflection that occurs at walls and windows.

Bartholomew and Zaldívar Pérez[116] suggested that mass psychogenic illness might have been responsible for igniting symptoms of an attack. An interesting analogy occurs when fish are tested as individual subjects, one-at-a time, for a response in the field (e.g., startle, or change in direction or speed of swimming, in response to an acoustic deterrent) that actually depends on a group effect, where the response of one individual affects others, and reinforcement occurs (Section 7).

THE TIMES SATURDAY NOVEMBER 2 2002

US Navy furious after judge bans sonar that harms whales

From James Doran in New York

ENDANGERED whales and enemy submarines have been saved by a Californian judge, who has banned a new naval sonar device.

Elizabeth LaPorte, a magistrate in San Francisco, imposed a worldwide ban on an ultra-low frequency submarine detector recently introduced by the US Navy after environmentalists claimed that the booming noises the device emits could cause irreparable damage to marine mammals.

The sonar device is designed to blast the ocean depths with ultra-low-frequency sounds that can detect the quietest submarines up to 300 miles away.

The sound, which is apparently deafening to whales, is broadcast from 18 powerful speakers dangling in the sea on cables behind naval vessels. The 215-decibel bursts flood the ocean, causing confusion among whales and other big sea creatures that use similar sonic booms to find food and sexual partners.

The effect of the device when deployed in breeding and feeding grounds was described by one environmentalist yesterday as "rather like playing heavy metal music at full volume in church". Environmentalists had sought to ban the device after a recent increase in whale beachings across the world and an unexplained rise in whale deaths.

The US Navy declined to comment, but it is understood that admirals are furious with the decision because Navy destroyers were only in July granted a presidential order to "harass" a certain number of whales while testing the device.

But Joel Reynolds, a lawyer with the Natural Resources Defence Council, said: "There was no justification for giving the Navy a blank cheque to operate this sonar in 75 per cent of the world's oceans." If allowed to continue, he said, the sonar system would have "threatened marine life on a staggering and unprecedented geographic scale".

The Navy and environmental groups that filed the legal action have until November 7 to report back to Judge LaPorte with an interim solution. The National Marine Fisheries Service ruled in July that the device would have "negligible impact" on whales if it was used at least 12 miles from shore. The fisheries body also recommended that ships should shut it down if they spotted whales in the water.

Environmentalists sued soon after the report was published, however, alleging that the ruling violated a number of federal laws designed to protect wildlife. In her 58-page report, Judge LaPorte decided that federal officials had failed to identify off-limits zones for the new sonar device, where endangered species of marine mammal are known to dwell.

The Navy says that setting up such zones could be exploited by an enemy.

Figure 8. Cutting[153] from The Times newspaper, 2 November 2002.

Those working in the field of the effects of anthropogenic noise on aquatic life will be aware of the publicity in the media of those adverse effects. In the 1990s there were speculative claims in both directions, from those denying any effect, to those saying the likely effect would be warranted or negligible (Figure 8), to those who claimed that all marine mammal mass strandings had their origins in anthropogenic sound (despite over a century of written history of strandings prior to the advent of sonar and seismic surveying). Sage assessment of the loudness of underwater sounds is regularly confounded by the confusion[154] created when media, politicians, courts and even scientists fail to apply a conversion when comparing dB in water to those in air (the standard 61.5 dB conversion[155-157] accounts for physical factors, such as the use of different reference levels and the differences between the density and sound speed in air and water; however it fails to take into account subjective factors such as annoyance)[155,156]. Examples include the description of sonar as being “as loud as 2000 jet engines”[158]; and when academics (who had taken into account only the use of differing normalization intensities in air and water, neglecting the differences in density and sound speed) produced erroneous calculations which led to media suggestions that the sound of the penis of a 2 mm-long freshwater insect, the lesser water boatman (*Micronecta scholtzi*), rubbing against its abdomen underwater “reached 78.9 decibels, comparable to a passing freight train”[159]. Mistakes also include comparing the level heard in air at the microphone or ear, with the source level routinely cited for underwater sources (often found by measuring the sound level at some distance and then correcting for attenuation to allocate to the source the SPL it would have had 1 m from the source, had that source been a point source): such comparisons are not germane unless the source is indeed a point source, and the microphone is indeed 1 m from it. Further mistakes can be made if it is not recognized that the sound level for the property that is being measured (e.g., AEP in fish; temporary hearing threshold shift in humans) may differ from that which produces the effect that should be of interest (a behavioral response in fish; annoyance in humans).

As the UK enters a period of renegotiation of its waters with the EU, and there exists the possibility of a cessation of Scotland from the UK, the rights to stocks of fish and shellfish is already a hot political issue, with Scottish boats catching relatively little from zone VII, and zone IV dominating for all parties (Figure 9)[160]. The message of this section is not that the media can accidentally or deliberately mis-represent research, such that scientists should take care when making statements to them: this is well-known. Rather, it is perhaps that, even with access to the history that this happened in the 1940s, the parties were prepared to do the same again when it came to Cuba and, even with the knowledge that international relationships were at stake, authors and editors opted for publication despite unorthodox statistics. We cannot know how the reviewers felt. We know the editors felt strongly enough to publish an editorial accompanying the research paper, where they state: "The primary value of publishing case reports and case series in the medical literature involves the documentation of symptoms, signs, and clinical data in a unique group of individuals. Often at the time of initial report, the fundamental etiology and pathophysiologic mechanism underlying the clinical phenomena are not yet fully understood, but the clear description of potentially pertinent data serves as a foundation on which other clinicians and investigators can build." They go on to give reasons that might have suggested delaying publication until a fuller analysis could be written, including that: "it remains unclear whether individuals who developed symptoms later were aware of the previous reports of others. Furthermore, the quantitative results for specific tests (e.g., neuropsychological tests) are not yet available for all affected patients, so independent assessment as to the scope and severity of deficits among all individuals remains challenging... The initial clinical evaluations were not standardized and examiners were not blinded, which is important given that several of the abnormalities reported in the article (e.g., eye movement and balance dysfunction) were based on patient self-report or involved at least some degree of subjective interpretation by the clinician performing the examination". They then go on to confuse the issue by introducing the use of focused MHz ultrasound to generate brain lesion, failing to note that this cannot be achieved when the ultrasound passes through air. Given the wide attention in media and political circles, they perhaps felt pressure to publish an incompletely analysed study to clarify the state of affairs, but this was only partially successful.

Takeaway: The statistics can fail to show an adverse effect, but this must not be interpreted as statistically failing to show an effect can occur.

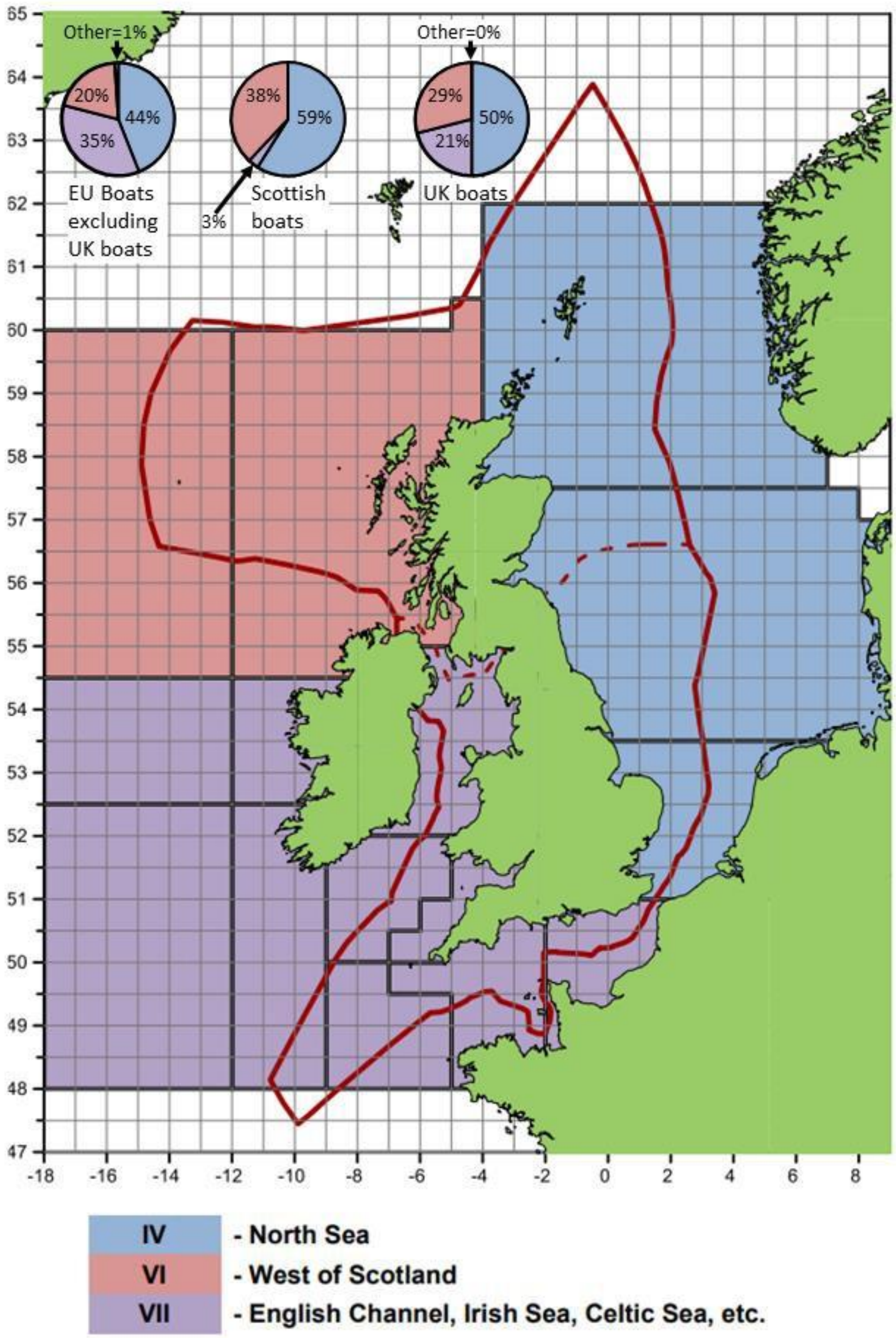

Figure 9. The United Kingdom's Exclusive Economic Zones in relation to ICES (International Council for the Exploration of the Sea) subAreas IV, VI and VII. The Divisions within each sub-Area and the ICES statistical rectangles are also shown. (EEZ based on Admiralty Chart No. Q6353.) The three pie-charts at the top show the estimated values of fish and shellfish landed from the United Kingdom EEZ by (a) all EU fishing boats (excluding UK boats), (b) by UK boats, and (c) by Scottish boats (bottom) by area of capture: ICES sub-Areas IV (North Sea), VI (West of Scotland), VII (English Channel, Irish Sea, Celtic Sea, etc.) and other areas. (Annual average catches from 2012 to 2014). The "other" ICES sub-area zones sub-area zones in the analysis consist of: zone II (Norwegian Sea); zone V (Faroe); and zone VIII (Bay of Biscay). Data from Napier.[160]

11. CONCLUSIONS

A perspective on one field by another, using different frequency ranges, media, and organisms, is idiosyncratic. It has identified many features that, on reflection, appear obvious. However the importance of the exercise is to facilitate keeping those features in mind when faced with a growing field that, with limited resources, must make use of received wisdom, and low-hanging fruits, and push for standardization: these are all extremely useful, but come at a cost, and if a pragmatic stance is taken to progress the field in a timely and cost-effective manner, not all those costs will be paid. This is how we reach the current stage of confusion with the exposure of humans to airborne-VHF/US. It is vital that fields are periodically revisited to question and perhaps replace the legacy, the received wisdom of experts in the field, and the established guidelines that are self-proclaimed by standards bodies as 'interim', and leave them as the sole arbiters of human exposure without revisiting them for 35 years. Bodies with a duty to set and maintain standards and guidelines, who must steadfastly resist changing them to suit the needs of each new 'customer' in order to provide the community with a common basis that has had time to disseminate into practice, must recognize that that duty comes with an obligation to limit the required inflexibility such that it does not allow errors to propagate when they are revealed to be erroneous.

Finally, this is a plea for the wide perspective. Each of us applies our own filter when assessing and organizing a field, and the process of thinking about two disparate disciplines simultaneously lays this bare: what reader of this article would not think 'this material would belong better in a different section' or 'this material would be better omitted'? These are understandable responses even from those embracing multidisciplinarity (and those that do not, will be reading introductory material from their own discipline that is intended for readers from the other discipline, and reading material from another discipline that holds little interest to them). There will be opinions that are both valid and contradictory. We try to tread the path of objectivity in science, but each of us wears our own subjective shoes. As such, at times the 'right approach' can be mythical, because there are many, none of them perfect. This highlights the importance of multidisciplinarity. The scientific profession tends to force us into narrow silos, so that even a discipline that started as a multidisciplinary field can evolve into silos, a set of common practices and shared wisdom. Whilst these are unquestionably useful to enable progress, they must periodically be questioned, and action be taken to adjust practices as indicated by new knowledge.

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