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Issues relating to the use of a 61.5 dB conversion factor when comparing airborne and underwater anthroprogenic noise levels

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Abstract

Although a considerable amount of the current underwater acoustics literature deals with the proper documentation and analysis of underwater anthropogenic noise levels, mistakes and misconceptions can occur when attempts are made (often by non-experts) to make these data accessible for legislators, journalists and the public. This is because it is difficult for humans to assess qualitatively underwater sound level and quality. It can even be difficult for researchers to judge whether a given underwater sound should be classified as "loud" or "soft". Many practitioners have suggested that the difference between airborne and underwater sound can be accounted for by applying a 61.5 dB comparison factor (in an attempt to compensate for the different acoustic impedances, and dB reference level conventions, which characterize acoustics in air and water). Whilst use of such a factor is preferable to use of none (which has led to misleading comparisons between levels in-air and water) nevertheless its existence could confer a false sense of security that the comparison is sound, whereas in fact, depending on the details of the comparison, a range of other issues would have to be rigorously taken in to account. Those issues include the perception of sound and annoyance underwater, and the problematic issue of making comparisons across species. This paper does not offer solutions to those issues, but rather outlines the thinking behind the 61.5 dB comparison factor, and shows the intriguing results of it blind application in some interesting example scenarios.

Keywords: Underwater acoustics; Sonar; Decibel; Anthropogenic noise; Snapping shrimp; Bearded seal; Bottlenose whale; Strandings; Marine mammals; Cavitation in cetaceans

1. Introduction

Media coverage of cetacean activity, including the stranding of a beaked whale in the Thames River [1,2] and the occurrence of several mass strandings off Cape Cod during winter 2005–2006 [3], often highlight for the public the importance for the scientific community to continue to research and document the relationship between marine mammals and sound [4]. However, despite advances in instrumentation for measuring sound in water, and progress in understanding how marine animals perceive sound, it still remains difficult to answer a basic question: How loud is "loud"? This paper will not seek to address this question, nor that of how underwater sound is perceived by marine life. Rather it will explain the most common form of correction factor used in converting from airborne to underwater sound levels, and use example situations to show how blind calculations using this correction factor can generate intriguing results.

The last decade has seen an explosion in research which has the primary motivation of studying anthropogenic noise in an attempt to understand how marine fauna perceive and extract meaningful acoustic information from their environment. Of particular particular concern are the harmful effects of anthropogenic noise on cetaceans; especially the interruption of acoustic transmissions by cetaceans, or the inadvertent production of acoustic trauma in marine mammals [5]. Whilst underestimation of the potential effects of anthropogenic noise carries

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obvious risk, so too does overestimation. This is because, whilst the elimination of anthropogenic noise would be an unrealistic goal, a cooperative strategy for minimising the risks must be based on realistic and trusted procedures for assessing the effects of the noise. It is essential to be accurate with the facts if the community of those 'stakeholders' with an interest in sonar (both those who use sonar and those who seek to minimise any deleterious effects) are to work together to prevent harm by sonar, whilst preserving the considerable benefits that can accrue from safe use of sonar. Similar comments apply to other applications associated with the generation of underwater sound, such as the operation of off-shore wind-farms, refineries, shipping, piling, dredging and quarrying activity.

Unsafe comparisons using dB-scales are prevalent, and misleading to legislators, journalists, and the public (see Section 2). Avoiding the errors inherent in such poor comparisons, some researchers and practitioners [6–8] have recommended a 61.5 dB conversion factor to convert between underwater and airborne sound levels. In this paper, the concepts behind the 61.5 dB conversion factor are considered (Section 3). Then, a series of examples are introduced to illustrate for the reader ways in which even this conversion factor can bring about counterintuitive comparisons (Section 4). It is, of course, important to appreciate that intuition forms no rigorous basis for judging how sound is perceived underwater by non-humans, and so the counterintuitive nature of the outcomes to the examples in this paper should not be taken as proof of concern. However, counterintuitive outcomes to the 61.5 dB comparison factor are important since (i) by far the overwhelming number of judgements made by the public on the issue of marine mammal welfare with respect to noise are erroneously based on intuition; and (ii) one of these counterintuitive outcomes is not the result of any cross-species comparisons, but rather between sound perception by humans in air, and humans in water (Section 4.2.1).

2. Confusion regarding the decibel

Much of the misreporting of anthropogenic noise stems from a misunderstanding of the differing traditions and practices for applying it in air and water, and the difficulty of relating the physical measures to subjective effects across species [9,10]. The simplest and commonest error is the poor practice of implying that the decibel scale is an absolute measure, which becomes undeniably erroneous when transferred from air to water. The sources of other misunderstandings are less transparent, as this paper will outline.

The unfortunate side-effect resulting from the publication of misleading statements regarding the decibel is the potential for the public to misperceive the effects of sonar on marine life. Pressure from an ill-informed public can then be placed on government, advisors and legislators. In the case of the links between common sonar practices and marine mammal stranding, comparisons between the sounds heard by cetaceans in the presence of sonar, and the sounds heard by humans in the presence of turbomachinery and/or space rockets, are not uncommon. Consider for instance a statement in a press release published by the National Resources Defence Council (NRDC) [11] (a US-based environmental lobby group) in October 2005: "Mid-frequency sonar can emit continuous sound well above 235 dB, an intensity roughly comparable to a Saturn V rocket at blastoff". In an excellent critique, Chapman and Ellis [10] analyse a 1998 quote from *The Economist* [12] which arose following scientific correspondence in *Nature* [13]. Referring to a sonar source designed to produce low-frequency sound, *The Economist* stated that "It has a maximum output of 230 dB, compared with 100 dB for a jumbo jet".

Just as it is beholden on users of the dB scale always to cite their reference pressures and the location of the measurement with respect to the source, so too should it be obligatory for those who make comparisons between levels in water and those in air to state the procedure used for the conversion. Whilst the differing reference pressures and acoustic impedances of air and water make nonsense of a direct uncorrected transcription of dB levels from water to air, the 61.5 dB correction factor recommended by many [6–8] cannot be seen as the sole requirement in comparing, for example, annoyance levels between species. Indeed, its use even within a single species can lead to unexpected predictions (Section 4.2.1). Section 3 will outline the logic used to justify the 61.5 dB correction factor.

3. Deriving the 61.5 dB conversion factor

Generally, underwater acoustic data are expressed in decibels with reference to 1 μPa, whilst air borne noise data are referenced to 20 μPa (rms levels will be used throughout this paper). The transfer from dB re 1 μPa to dB re 20 μPa is straightforward, by letting the rms pressures P_2 and P_1 in Eq. (1) take their respective values:

$$10\log_{10}\left(\frac{P_2}{P_1}\right)^2 = 20\log_{10}\left(\frac{1\ \mu\text{Pa}}{20\ \mu\text{Pa}}\right) = -25.5\ \text{dB} \tag{1}$$

where P_1 is the reference pressure in air, and P_2 is the reference pressure in water. However, it is not sufficient simply to subtract 26 dB from an underwater level to make a viable comparison to an airborne sound. The specific acoustic impedance of water (given by the product $\rho_w c_w$, where ρ_w and c_w are respectively the density and sound speed in water) is some 3600 times greater than that of air. If the critical physical quantity which must be compared between air and water is based on the acoustic intensity[1] (see Section 4.2), then a further correction factor of 36 dB is required, because:

$$10\log_{10}\left(\frac{\rho_w c_w}{\rho_a c_a}\right) = 10\log_{10}(3600) \approx -36\ \text{dB} \tag{2}$$

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[1] For the purposes of such calculations, the acoustic pressure falls into this category.

where ρ_a and c_a are respectively the density and sound speed in air. The values used in Eq. (2) are: $\rho_w = 1000\ \mathrm{kg\ m^3}$, $c_w = 1500\ \mathrm{m\ s^{-1}}$, $\rho_a = 1.21\ \mathrm{kg\ m^3}$, and $c_a = 343\ \mathrm{m\ s^{-1}}$. Taking the sum of the two 'correction' quantities given by Eqs. (1) and (2), one might draw the following conclusion: to convert between an underwater sound measurement and its airborne equivalent, the underwater level referenced to 1 μPa should be lowered by 61.5 dB and the reference then simply switched to 20 μPa. In discussing this widely used conversion, Gisner et al. [14] are helpful in pointing out that the very justification for the use of the conversion introduces difficult questions. They state that: "One of the most interesting aspects of hearing in marine mammals is the fact that anatomically they follow much of the basic land mammal pattern, but they have also solved the fundamental problems of how to hear in water including the attendant complications for acoustic cues; e.g., increased pressures and shortened interaural arrival times".

The dB value used in (1) and (2) is based on the ratio of time averaged squared pressure (acoustic power) expressed through the root-mean-squared (rms) value of the recorded pressure signal. Such time averaging is well-defined in the context of continuous sounds, but this is not so for transient sounds, such as odonotocete echolation clicks and short duration sonar pulses. For such signals, the period over which the time averaging should be performed is a matter of convention and can significantly affect the results obtained [15]. To overcome this, some workers [16,17] choose to use a definition of the dB based on the peak-to-peak value in a waveform, which is unambiguous and easy to measure, but can lead to inflation of the cited dB value. For example Au [18] demonstrates that the peak-to-peak and rms definitions of the dB can lead to results that differ by more than 15 dB for a dolphin echolocation click. Madsen addressed the difficulty encountered when using different time/amplitude criteria for establishing reported levels in detail [16]. There is no universal correction that can be applied to convert between rms to peak-to-peak measurements, for two reasons: first, there is no absolute definition of rms values for transient signals; and second, in general there are many signals that have the same rms level, but different peak-to-peak values. Richardson et al. word this as follows [19]: "It is difficult to compare any of these values with levels from continuous sources, which are normally expressed on a "root-mean-square" (rms) pressure basis. For an ideal sinusoid, the rms level is 9 dB lower than the [peak-to-peak] value and 3 dB lower than the [zero-to-peak] value. However, seismic and other impulses are not ideal sinusoids, so any simply conversion formula is approximate".

Indeed the very usefulness of the dB scale (in reducing the sound field to a single number) can be its undoing. Even when the need for ancillary information (reference pressures, the location with respect to the source that the cited level refers, the medium in which the measurement is taken, etc.) has been recognised, and the caution against applying anthropocentric judgements of perception to non-humans has been heeded, the very philosophy of using a single number to encapsulate an acoustic signal is too simplistic. The preceding paragraph discussed examples where differences in the time-domain make expressions on the dB-scale difficult. One could go further, and say that it can be unsafe to hide those differences by use of a dB-scale in place of a waveform.

Consider for example the single issue of the possible mechanisms for bubble formation in cetacean tissue as a possible result of exposure to sonar [20,21]. Certain mechanisms for bubble growth, such as rectified diffusion [20–22], can take timescales over many acoustic cycles to become significant. However, gas bubbles in liquids and tissue tend in general to have pulsation natural frequencies which vary roughly inversely with their size, such that the microscopic bubbles envisaged for tissue would have characteristic response times very much faster than the acoustic period of naval sonar. As a result, there are other bubble growth mechanisms for which the important timescale is less than one acoustic cycle [23]. A transient acoustic signal might be very significant with respect to the fast-response mechanisms, but insignificant with respect to those which take many cycles to generate bubble growth. Eliminating the temporal characteristics of the sound from the information by expressing it as a single decibel number could remove key information, not simply for bubble growth, but for a whole range of subjective and physical responses to sound which differ in terms of the relevant timescale for significant effect (including annoyance, masking, hyperthermia, radiation forces, streaming, cavitation, microstreaming, etc.) [15].

In similar vein, reduction of an acoustic signal to a single decibel number eliminates frequency information. Not only is this information important because many subjective and physical effects depend on the frequency, but the bandwidth over which energy is considered for inclusion in the decibel calculation is important. Even when just our best-characterised species (*homo sapiens*) is considered, whilst the A-weighted sound level is (according to Kinsler et al. [24], 1982) "the simplest and probably most widely used measure of environmental noise", it will ignore any energy in the infrasonic and ultrasonic regimes, which may generate adverse effects in humans [15]. Hence two sound fields, with the same dB(A) level, may represent very different hazard to humans, and yet not to use the A-weighting would fail to make any allowance for the sensitivity of the human ear to the various frequency bands. Given furthermore that such weighting scales were generated through measurements on statistically representative populations, comparisons and extrapolations to assess the impact on non-human individuals cannot be simply done at this time. Certainly dB(A) measurements have no relevance if the species in question is to be affected by sound in either the infrasonic or ultrasonic regimes.

In summary, researchers often attempt to describe underwater anthropogenic noise in terms similar to those used to describe the effect of in-air anthropogenic noise on people. Gisner et al. [14] have pointed out that such an approach might be fundamentally flawed, in that researchers should first understand the way in which cetaceans extract information from acoustic waves, before attempting to quantify how new sounds might interfere with the process. The following section will consider some fundamental differences between the sound in air and sound in water, and the way in which those sounds tend to be described.

4. Sources of discrepancy for in-air and underwater sound level comparisons

4.1. Source level vs Sound pressure level

In acoustics, the distance from a source at which a particular measurement was taken is critical information. In a free-field in air, sounds usually decay 6 dB for every doubling in distance from the source [25]. If a dB level is quoted in air without reference to range, it is generally assumed to refer to the sound pressure level at the point of interest (e.g.the human ear). However, the convention is different in underwater acoustics, where sound levels are generally reported as "source levels" e.g. the level at 1 m from the source. This is done because the environment is vast and the point of interest is uncertain, and because modelling of the propagation is crucial because, for example, refraction could cause the sound pressure to increase locally as one moves away from the source.[2] However, the uninitiated can confuse the source level (1 m from the source) with sound pressure level at the point of interest (e.g. the fauna), and incorrectly infer that the fauna are exposed to much higher levels than actually occurs.

If a reported underwater sound pressure level measurement was observed or back-calculated to some distance other than one meter from the source, then that distance will almost always be supplied. Just as it is incumbent on users to state the dB ref when sound pressure levels are cited, so too should they state the measurement position to which the cited dB level pertains. The only exception should be when source levels (rather than sound pressure levels) are stated, as the reader should be aware that this pertains to a range of 1 m.

Even this simplifying convention can lead to misunderstandings, because the concept of back-calculating a level back to the source location can be problematic if the information is not well understood. Consider a deep water source array consisting of three omni-directional, continuously operated, closely-spaced[3] acoustic drivers, each of source power 200 dB re 1 μPa at 1 m. If the source array geometry is known, the signals from the source add coherently (as they would be expected to do if the output signals were identical), and an observer in the acoustic far-field[4] measures the sound level emanating from that array, then the sources can be treated as a theoretical single source with a power of 205 dB re 1 μPa at 1 m. The sound pressure 1 m from such a theoretical source, would indeed be 205 dB re 1 μPa at 1 m. However, for the case of our example involving a 3-source array, if the elements are arranged in a line, and the driving frequency is sufficiently low so that the source spacing is greater than about a 0.7 m ($f_{\text{driving}} < \sim 2.1$ kHz), then there is no region in the water where the level is actually 205 dB re 1 μPa [26]. So it can be seen that back-calculating to find the source power can of an array, if misinterpreted, give inflated estimates for the sound pressure in the array near field. Indeed characterisations of this type are used to describe sonar systems such as those to which the NRDC claim in Section 2 pertain.

In the case of the claim by NRDC that mid-frequency sonar is roughly comparable to a Saturn V rocket at blastoff, the comparison is difficult to justify. Attempts have been made to measure the sound radiated by a rocket. However, the sound power of a rocket booster is difficult to estimate as a result of the nonlinear characteristics which govern propagation away from the source. McInerny and Ölçmen [27] measured the noise from a Titan IV lift-off at a site located 0.82 km from the launch pad. Bearing in mind that no reference measures for the levels emitted by Saturn V rocket exist, it could be argued that these Titan IV measurements represent the most reasonable substitute.

It would of course be possible to use the 61.5 dB conversion factor in an attempt to compare the rocket noise with the level from mid-frequency sonar at the same distance (0.95 km). However, even when the comparison is tempered with the recognition that possibly vital physical factors (nonlinear propagation, near field and evanescent effects near the source; convergence zones in the ocean, etc.) are not concluded, it is nonsensical to suggest that such a calculation can compare how detrimental those sounds are. This is because the sound quality is very different in both cases, and such subjective judgements as 'louder', 'quieter', 'annoying', etc. are difficult to make when the species in question, and its behaviour and location, are known, let alone for assessment of the unknown species.

McInerny and Ölçmen [20] measured the noise from a Titan IV liftoff at a site located 0.82 km from the launchpad. A maximum level of 139.9 dB re 1 μPa (3 Hz–15 kHz, 1-s averaging window) was observed when the shuttle was at an altitude of approximately 0.48 km, at a range of 0.95 km from the receiver. For a comparison of

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[2] An important feature which can negate the simplistic assumption that an animal will move away from a loud source, even before the other drivers influencing its behaviour are considered.

[3] "Closely-spaced" is used here to indicate a separation on the order of a wavelength.

[4] As defined in terms of the source separation distance. For this argument, "very far" corresponds to the acoustic far-field, meaning a distance of at least 10 wavelengths from the source array midpoint.

the level from mid-frequency sonar at the same distance (0.95 km), we the following use [24]:

$$L_{\text{observed}} = L_{\text{source}} - 10\log_{10}\left(\frac{r_{\text{observed}}}{r_{\text{ref}}}\right)^{\xi} \tag{3}$$

where L_{observed} is the level observed as some distance r_{observed}, and L_{source} is the level of the source as observed at the reference distance r_{ref}. The exponent ξ, which accounts for spreading, is set equal to 1 in the case of purely cylindrical spreading, and 2 in the case of purely spherical spreading. Practitioners often apply $\xi = 1.5$ to account for the case wherein the spreading is neither purely cylindrical nor purely spherical, to account for 'semi-spherical' spreading [28]. Using 1 kHz as a working sonar frequency (where absorption is nearly negligible [29]), the sound level observed at 0.95 km from a source of strength 235 dB re 1 μPa at 1 m is shown to be ($\xi = 1.5$) 190 dB re 1 μPa. Assuming that NRDC use the 61.5 dB conversion factor to make their comparison, one obtains an 'equivalent level' of 128.5 dB re 20 μPa for the sonar, 10.5 dB less than the levels observed by McInerny and Ölçmen for the Titan IV rocket. Under inspection, it then seems that it is unfair to say that mid-frequency sonar is roughly comparable to the sound generated by a rocket shuttle at lift-off.

4.2. Equivalent loudness

In understanding how intrusive a particular sound might be to a human-occupied environment, sound level is certainly not always the most important factor [30]. In fact for humans, "...it is mainly the indirect effects of noise and vibration on people such as long-term annoyance, interference with various activities, and possible health effects that are important, and not the actual levels of physical energy *per se*" [31].

One early attempt to characterise a wide variety of in-air sounds using a single number was through the introduction of the concept of loudness. The loudness level for a given sound is the level at which a 1000 Hz control tone must be played in order for an average listener to perceive the sound as being as loud as the control tone. Loudness levels have been incorporated into a method for assessing airborne noise using a frequency weighting scale known as the "noise rating", or NR, scale [26]. In the 1990s frequency weighting was proposed as a method of assessing analytically how a given sound might be perceived by humans underwater [32–34]. Such studies were only possible because they built on decades of statistically valid data on the hearing and perception of humans in air. Following this worthwhile innovation, because it appeared that frequency weighting was simple to implement, others attempted to extrapolate this technique to characterise the hearing of non-human marine creatures for which no comparable statistically valid database on acoustic perception exists [35]. Through such extrapolation, some investigators have compiled recommendations for marine loudness curves based on inverted auditory frequency sensitivity data for various animals (similar to the A-weighting methods discussed in Section 3) [35–39].[5] Such methodologies should be treated cautiously: the animal data is far sparser than that required to characterise 'normal' human hearing in the population; some of the assumed transposition from human in-air hearing to animal in-water hearing lacks validation; and indeed it has been shown that A-weighted sound pressure level can be inversely related to both loudness and annoyance [40]. Although such frequency contours remain in wide use, the current shortcomings of weighting networks will make them inappropriate for use in generating specific guidelines or recommendations for non-humans, as some recommend, particularly as the probity of such guidelines cannot be validated with our current level of knowledge. However, when applied cautiously in-air for humans, they can give insight into which types of sounds are annoying, particularly when those sounds are relatively broadband and steady-state [26]. From this perspective, a weighting network is now introduced in an example which keeps the consideration within the human species (humans in-air and humans underwater) to show a further intriguing consequence of using the 61.5 dB conversion.

4.2.1. Snapping shrimp on the NR scale

Consider the underwater noise that would be encountered by a human swimming in warm coastal water, such as that heard by a snorkeler near a tropical coral reef. This will now be translated into an in-air equivalent as expressed by the noise rating curves. In such an environment, the ambient acoustic spectrum is often dominated by so-called 'snapping-shrimp', in reference to a family of crustaceans, *Alpheidae*, in the genus *Synalpheus* [41]. The distinctive crackle made by snapping shrimp, which has been described as being comparable to the "frying of fat" [42], has been researched by several investigators. In their 1948 paper, Everest et al. [43] recorded an acoustic spectrum, a portion of which is shown as white bars in Fig. 1 depicting the sound pressure levels in octave bands between 200 Hz and 8 kHz.

The first stage in adjusting these measured levels (the white bars) is to undertake a correction for the change in decibel reference value (Eq. (3)). The result is shown in gray in Fig. 1. The next stage is then to adjust these grey bars further, to account for the difference in specific impedance between water and air (Eq. (2)). The result of this procedure is shown in black in Fig. 1. The spectrum is then

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[5] It should be noted that, before applying the 'dolphin-weighting' (dB_{dt}) Goold and Fish [34] were careful to note that "there is some difficulty in determining how loud the seismic pulse seems to a dolphin at different ranges. This stems from the fact that hearing threshold measurements have been carried out using long (quasi-continuous) tones and tone bursts of varying duration but not for more complex signals such as the seismic pulses and (equal loudness) curves have not been measured at all".

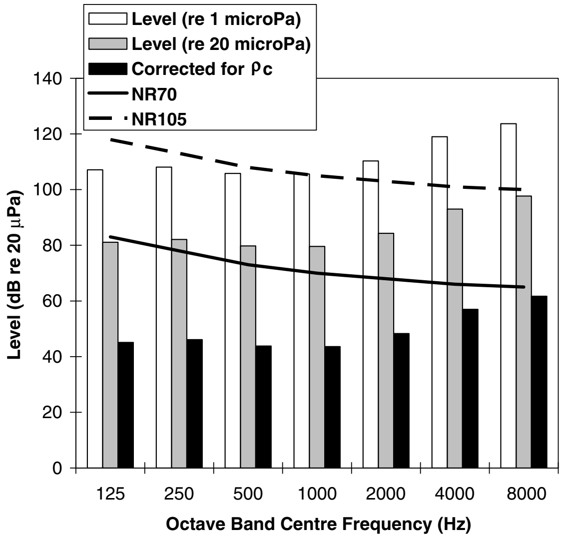

Fig. 1. This figure uses the noise rating curves to shows why it might be inappropriate to suggest that subtracting 61.5 dB from an underwater sound pressure level "converts" that level to its airborne equivalent. To make this comparison as transparent as possible, the levels in each octave band are shown at three separate points during conversion. In white bars are shown unadjusted levels recorded in Kaneohe Bay by Everest et al. [43], where the ambient acoustic spectrum is dominated by snapping shrimp. To account for the fact that most acoustic measurements performed in water are referenced to 1 μPa, while those performed in air are referenced to the human threshold of hearing at 1 μPa, 26 dB is subtracted from the original levels to give the octave band levels illustrated by the gray bars. To account further for the difference in the specific impedance ρc from air to water (1.5×10^6 Pa s m^{-1} to 415 Pa s m^{-1}), the octave band levels are reduced by an additional 36 dB, for a net reduction of 61.5 dB per octave. These results are shown as black bars. The calculation indicates that according the conversion method indicated, the audible crackle of a coral reef might be rated as NR 70; a level described in the Maritime and Coastguard Agency standard for good noise practice as being the maximum allowable in the control space for the machine room of a ship [44].

displayed against the noise rating curves to give an equivalent airborne Noise Rating. This method, while unorthodox, illustrates an important point. The final 'converted' values (the black bars in Fig. 1) suggest that the ambient acoustic spectrum encountered by an observer in the water above a coral reef is comparable to NR 70. Interestingly NR 70 is the guideline for maximum acceptable noise level set forth by the UK Maritime and Coastguard Agency for the machine control room aboard a ship [44]. That is to say, either the in-water noise generated by shrimp in a coral reef, as heard by holidaymaker snorkling above it, is comparable to an industrial environment, or the standard practice of subtracting 61.5 dB from an underwater sound level to give its airborne equivalent is overly simplistic to the point of distortion even for rough attempts at assessing annoyance for humans. Although such subjective comparisons are not rigorous, they indicate that it is no simple matter to transfer 'annoyance' levels of sound from one medium to another, even when we restrict it to one species: to make such comparisons with the added dimension of interspecies transfer included (as is frequently done between humans and cetaceans) would be unwise in the extreme.

Fig. 2. A bearded seal (*Erignathus barbatus*), Bering Sea, May 1979. Photo taken by Captain Budd Christman and made available through the NOAA online photo library.

As a point of information, snapping shrimp are known to generate noise up to at least 200 kHz [45]. However, the argument presented here is concerned with a method of assessment for human perception of noise (the noise rating, or NR, family of curves in this case) which does not include sounds above the 8 kHz octave band, so acoustic energy above that range has been neglected. This same noise perception assessment method specifies that acoustic information down to and including the 63 kHz octave band should be used to assessment, but detailed data regarding low frequency noise production snapping shrimp are not widely available. As such, the 250 Hz octave band is the lowest included in this study. The net result of these effects is to make the NR 70 assessment of shrimp noise a conservative one. Note that the involvement of the snapping shrimp in this NR calculation is only as a sound source. An important message from this paper is to avoid making casual cross-species and anthropocentric conclusions.

4.2.2. Bearded seal calls

One of nature's astonishing feats of acoustics belongs to the bearded seal, *Erignathus barbatus*, pictured in Fig. 2. While diving in Arctic waters, the bearded seal sings a song which has been recorded as achieving back-projected source-levels as high as 178 dB re 1 μPa @ 1 m (i.e. source level) [19]. The prolonged sounds[6] produced by this extraordinary animal (bearded seal calls often last several seconds [46]) extend from 20 to 6000 Hz, with peaks in the range from 1–2 kHz. Using the 61.5 dB conversion factor, and recognising that most of the acoustic energy

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[6] A recording of the bearded seal song can be found on the webpage Bioacoustics Research Program of the Cornell University Lab of Ornithology, available at http://www.birds.cornell.edu/brp/SoundsMarMamm.html.

produced by this type of seal lies within the audible range (20 Hz–20 kHz [26]), one might arrive at the conclusion that the song of a bearded seal is approximately equivalent to an airborne sound of 116.5 dB, or roughly the level experienced a few feet from the loudspeakers at a very loud rock concert. The authors will not speculate whether in fact a bearded seal is as loud as a rock concert, but instead call attention to the fact that this is the unexpected conclusion drawn by applying the conversion factor in an uncritical and unquestioning manner.

There is another feature which is critical to understanding the extent to which a given sound is disturbing to a given person. This, specifically, is the previous experience the listener has had with sounds of that type [47]. It is short-sighted to expect that the study of human-made transients with respect to oceanic ambient noise spectra will reveal the extent to which a given transient might be perceived as being annoying. The comparisons made by researchers between naturally-occuring acoustics transients and active sonar emissions present the opportunity for fair benchmarks. Quantitative statistical work in this field might well facilitate the establishment of safe and usable standards for active sonar emissions in waters known to be occupied by cetaceans.

5. Conclusions

The complexity of issues relating to noise in water has made it tempting to characterise complex sounds with use of single number metrics. Myriad subtleties make it difficult to convert underwater sound levels into useful, single-number metrics. Identified as being problematic in this paper are two methods: the 61.5 dB conversion in conjunction with rms, peak-to-peak, and zero-to-peak levels; and frequency weighting. The 61.5 dB conversion can be more confusing than it is enlightening, in that it can give humans, who are air-based hearers, a false sense of security when working with figures describing underwater sounds. Frequency weighting techniques, which the scientific community has shown to be useful in certain situations on land, must be practiced with care. In particular, it is dangerous and misleading to apply frequency weighting using audiogram data derived from statistically insignificant populations.

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