Applied Acoustics 145 (2019) 137–143

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Practical implementation of auditory time and frequency weighting in marine bioacoustics

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ARTICLE INFO

Article history:
Received 8 May 2018
Received in revised form 19 August 2018
Accepted 27 September 2018
Available online 10 October 2018

Keywords:
Auditory frequency weighting
Auditory integration time
Marine mammals
Loudness
Behavioral reaction threshold
Dose-response function

ABSTRACT

Much effort is currently directed at describing the behavioral reactions of marine mammals following exposure to sound with the aim of deriving generalized thresholds and dose-response functions. The perceived loudness of a given sound is a candidate for a common metric for sound exposure. The loudness of a signal relates to various factors, including the stimulus duration and frequency content, and it can be approximated by an appropriate time and frequency weighting of the signal. Auditory frequency weighting is achieved by applying a frequency weighting function (band-pass filter), with a frequency response resembling the shape of an inverted audiogram. Temporal weighting may be achieved by computing the running rms-average (L_{eq}) with a time constant that is comparable to that of the mammalian auditory system. The practical implementation of such weighting functions are presented in the form of Matlab functions. These functions generate output signals that are weighted according to current recommendations for different groups of marine mammals. With these functions, it is possible to derive the weighted peak L_{eq} of a signal, which is likely to be a good proxy for the loudness of the signal. Ultimately, this weighted level is conjectured to be a predictor of behavioral response of marine mammals to the sound.

1. Introduction

A central concept in auditory psychophysics is loudness. Loudness is a measure of how loud a sound is perceived to be by the listener (human or animal), and is closely related to the intensity of the sound. Everything else being equal (i.e., for constant signal duration, frequency spectrum, envelope etc.), and for the same individual, there is a monotonic relationship between signal intensity and perceived loudness. However, as soon as other signal parameters change, loudness is likely to change as well, despite a constant signal intensity. If the frequency spectrum is changed, the change in perceived loudness is related to the shape of the audiogram and the fact that the sensitivity of ears varies across frequencies. The perceived loudness of short signals changes with changes in the duration of the signal, related to the temporal integration of the ear and the auditory pathway. This temporal integration phenomenon reflects the fact that the mammalian ear is better described as a detector of energy, rather than an intensity detector, for signals shorter than some hundreds of milliseconds e.g. [1–3].

Loudness is also a central concept for assessing the impact of noise on both humans and animals, and lies at the core of standards for human community noise regulation. These standards specify how measurements should be weighted, in both frequency and time, so that they reflect, as closely as possible, the perceived loudness of the noise under investigation (see [4] for a review of how auditory frequency weighting has developed in both humans and marine mammals). A seminal publication, with respect to marine mammals, was Southall *et al.* [5], which established noise exposure criteria for marine mammals. This publication provided the first systematic review of studies of temporary hearing loss in marine mammals and advocated the application of auditory frequency weighting in assessments related to marine mammals. More specifically, a series of "M-weighting" curves were derived, one for each of five functionally different groups of marine mammals [5]. The M-weighting curves have since been replaced by several iterations of new curves [6,7], which have been gradually adapted with the emergence of an increasing amount of new experimental evidence.

The marine mammal auditory weighting curves were originally developed to assess the risk of injury to individuals. In particular, they were developed to define group-wide exposure limits, based on the criteria of temporary and permanent threshold shifts (TTS and PTS). The original criteria [5], as well as subsequent ones [6,7], were formulated in terms of "sound exposure level" (SEL), which is a measure of total acoustic energy cumulated over the

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https://doi.org/10.1016/j.apacoust.2018.09.022
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duration of exposure (to some upper limit, currently 24 h), and weighted with an appropriate auditory weighting curve. This approach seems reasonable, as experimental data support weighted, cumulated SEL as the best overall predictor of likelihood of TTS [8,9]. Thus, auditory frequency weighting can be implemented by applying weighting to the frequency spectrum of the total signal that the animal is exposed to, and then summing the energy across the frequency spectrum, as described in Section 2.

In addition to criteria and thresholds for injury, it is also desirable, if possible, to derive generalized response thresholds for behavioral reactions to sound. However, this goal appears more difficult to achieve. Thus, even though it was one of the intentions behind the initial review [5], the authors refrained from providing actual thresholds. There are many reasons why this task is more difficult than deriving exposure limits for TTS/PTS. One of the difficulties is related to behavioral reactions being a continuum of many different types of reactions, and another the likelihood that behavioral responses depend on other factors than just loudness, such as context and physiological state of the animal e.g., [10,11]. However, it seems reasonable to conjecture some sort of general correlation (even if just on average) between the loudness of a sound and the likelihood of response to that sound. This approach has been suggested for harbor porpoises (*Phocoena phocoena*), supported by a review of experimental data from observational studies in the field [8]. Reaction thresholds were compared across several different types of sound sources (pile driving, seal scarers, and gill net pingers) by considering the integration time of the porpoise ear [8]. Integration time was included by adopting a correction factor, which was determined by the duration of the given sound, taking advantage of the observed relation between duration and thresholds for short sounds (below the time constant of the ear, roughly 125 ms), where the threshold decreases by 3 dB for each doubling of the duration. Similarly, when the spacing between pulses is much shorter than 125 ms, the threshold decreases by 3 dB for each doubling of the pulse rate (see [8] for further details). Comparison across sounds with different frequency spectra was achieved by comparing levels above the hearing threshold at the signal peak frequency (also known as sensation level), rather than comparing absolute sound levels. Comparing sensation levels is a crude way of performing an auditory frequency weighting with a curve identical to the inverted audiogram. However, while this approach works well for pure tone signals, it is less applicable to broad-band signals.

The key inference from [8] and the line of reasoning above is that, for a given marine mammal species, a generalized response threshold could be expressed in terms of loudness of the sound. A threshold expressed solely in terms of loudness is attractive because of its simplicity. However, this approach is limited as not all complexities of the responses may be captured. Such complexities are for example seen in several studies on larger baleen and beaked whales, which indicate that the distance to the source also could be an important parameter (see [12] for a recent example). Nevertheless, the conjecture of loudness being an important determinant in behavioral responses could and should be tested experimentally by measuring behavioral responses to a wide range of different sounds, and with thresholds expressed as estimated loudness of the received sounds. However, to do this, better tools to estimate the loudness of sounds, – by means of appropriate frequency weighting and temporal weighting of the signals, – are needed. Thus, this technical note describes a practical implementation of such tools. Two different functions are provided that perform auditory temporal and frequency weighting, respectively. These functions are described in general, as well as being presented in Matlab/Octave code. Complete source codes of the functions are included as electronic Supplementary material.

2. Weighting in the frequency domain – Auditory filter functions

A basis for the weighting of auditory frequency is recommendations of the U.S. National Marine Fisheries Service [7] (henceforth referred to as the NMFS recommendations). These curves are the result of a large review of all available experimental data to date and are thus adopted here without further justification. All weighting curves are described by the following general equation:

$$W_f = 10^{C/10} \cdot \frac{(f/f_1)^{2a}}{[1+(f/f_1)]^a[1+(f/f_2)]^b} \tag{1}$$

where f is the frequency in Hz, while a, b, $f1$, $f2$ and C are the species group specific constants listed in Table 1. Note, Eq. (1) differs slightly from the corresponding Eq. (1) in the NMFS recommendations [7] in that it is expressed here in linear units of power (for convenience), whereas it is expressed in units of dB in [7]. Fig. 1 shows the weighting functions for the five different groups defined by the NMFS [7].

For short signals, where one might only be interested in the frequency weighted cumulated energy of the signal ($L_{E,\ weighted}$), the weighting is performed directly on the power density spectrum or third-octave spectrum (whatever is relevant in the particular application) and $L_{E,\ weighted}$ is obtained by summing (integrating) across the entire frequency range. For the power density spectrum P (in linear units), $L_{E,\ weighted}$ is obtained as:

$$L_{E,\ weighted} = 10\log_{10}\int_0^{\frac{fs}{2}} P_f \mathrm{W_f} df \tag{2}$$

where fs is the sampling rate. For the third-octave spectrum $TOL(f)$, in units of dB re. 1 μPa, $L_{E,\ weighted}$ is found by summing across n third-octave bands, each with center frequency f_i:

$$L_{E,\ weighted} = 10\log_{10}\left(\sum_{i=1}^{n} 0.23 f_i W_f(f_i)\cdot 10^{\frac{TOL(f_i)}{10}}\right) \tag{3}$$

For longer signals, however, one might be interested in assessing the total $L_{E,\ weighted}$ of the signal and the instantaneous intensity of the weighted signal (i.e., the development of signal intensity with time). This is particularly important when frequency weighting is followed by temporal weighting, as described in Section 3 below. If one ignores the negligible phase distortion of the frequency weighting function, W_f, then the weighted version of a signal, s, can be obtained by the inverse Fourier transform of the product between the complex Fourier transform of the signal and the appropriate frequency weighting function.

$$s' = F^{-1}\{F\{s\}\sqrt{W_f}\} \tag{4}$$

Frequency weighting must be applied in linear units of amplitude (pressure), which is achieved by taking the square root of W_f (which has the unit of intensity).

2.1. Practical implementation of frequency weighting

A practical implementation of Eq. (4) in Matlab is provided in Supplementary material S2 in the form of a Matlab function "NOAAweighted". The central steps are described here. The function will accept as input, a real-valued signal, *sig*, sampled at a rate of *fs* (Hz), and will return the signal *sfilt*, which is the corresponding signal after it has been weighted by the selected type of filter (termed *filtertype*). Legal inputs for *filtertype* are 'HF', 'MF', 'LF', 'Otariid', and 'Phocid'.

s = NOAAweighted(sig, fs, filtertype)

Table 1
Constants of Eq. (1) for different functional hearing groups of marine mammals, according to the NMFS recommendations [7].

Species group	a	b	f1 (Hz)	f2 (Hz)	C (dB)
LF cetaceans (baleen whales)	1	2	200	19,000	0.13
MF cetaceans (larger odontocetes and most dolphins)	1.6	2	8,800	110,000	1.3
HF cetaceans (high-frequency specialists, incl. porpoises)	1.8	2	12,000	140,000	1.36
Phocid seals (true seals)	2	2	940	45,000	0.64
Otariid seals (sea lions and fur seals)	1	2	1,900	30,000	0.75

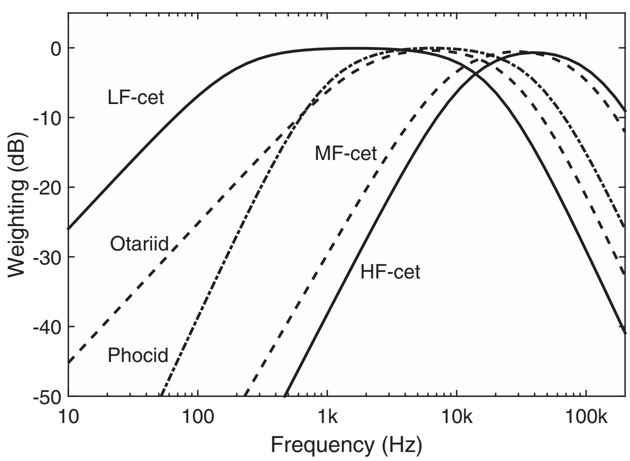

Fig. 1. Weighting curves (auditory filters) for five different functional hearing groups of marine mammals, as defined by [7] and given by Eq. (1) and Table 1.

The duration of the input signal must be long enough to contain several cycles of the lowest frequency that the animal is able to hear. Thus, for LF-cetaceans, it must be longer than 1 s (10 cycles at 10 Hz); for all other groups, it must be longer than 0.1 s (10 cycles at 100 Hz).

The appropriate weighting function is generated by evaluating Eq. (1) with the appropriate constants.

```
L = size(sig,1); %Impulse response length equal to signal length
f = linspace(0,fs/2,ceil(L/2))'; %frequency axis from 0 to the Nyquist frequency
W = sqrt((f/f1).^(2*a)./((1 + (f/f1).^2).^a.*(1 + (f/f2).^2).^b)*10^(C/20)); %Create filter response
```

The redundant half of the weighting function (the negative frequencies), which is needed to generate a real-valued output, is added by mirroring W_f around the Nyquist frequency (=*fs*/2).

```
W = [W ; flipud(W(1 + mod(L,2):end)]; %two-sided spectrum with zero phase
```

Finally, the transfer function is applied by elementwise multiplication of the Fourier-transformed signal with the weighting function. The weighted output is the inverse Fourier transform of the product.

```
s = ifft(W.*fft(sig)); %convolution of signal with impulse response
```

The filtered signal might be slightly longer than the original signal; therefore, in principle, it is advisable to add a few milliseconds of silence to either end of the input signal before filtering to avoid overspill in the time domain. However, the slopes of the filter functions are all very gentle; therefore, phase distortion and/or temporal aliasing can be ignored, except for very short signals (on the order of seconds or shorter).

3. Weighting in the time domain – auditory temporal integration

There is ample evidence that the vertebrate ear functions as an energy detector for short duration sounds [3,13]. Therefore, everything else being equal, the signal energy at the detection threshold remains constant as the duration of a sound increases up to some critical duration, which is termed the integration time. A large number of studies on many different vertebrate species have documented that this integration time is relatively constant across taxa, ranging from tens to hundreds of milliseconds (see, for example, data compiled by [14]). Within individuals, there is some variation in the integration time across different frequencies (for examples of marine mammals, see [15–17]). However, as a first approximation, a fixed integration time is assumed, as well as constant signal energy at threshold. The signal energy is given as:

$$E_\tau = \int_0^\tau \frac{p^2(t)}{\rho c} dt \tag{5}$$

where $p(t)$ is the instantaneous pressure, ρc is the acoustic impedance, and τ is the integration time. Conversion to the dB scale, using a reference pressure p_0 of 1 μPa, cancels out ρc to obtain the sound exposure level ($L_{E,\,\tau}$):

$$L_{E,\tau} = \begin{cases} 10\log_{10} \int_0^\tau \frac{p^2(t)}{p_0^2} dt (\text{analog signals}) \\ 10\log_{10}\left(\frac{1}{\tau fs}\sum_1^{\tau fs} p_i^2\right) = 20\log_{10}\sqrt{\frac{1}{\tau fs}\sum_1^{\tau fs} p_i^2}\ (\text{digital signals}) \end{cases} \tag{6}$$

The upper part of the equation is the continuous (analog) expression, while the lower part is the equivalent digital expression, where *fs* is the sampling rate. The unit of $L_{E,\,\tau}$ is dB re. 1 μPa^2-s. Note, the expressions on the right side of each equation are equal to the definitions of an rms-average (L_{eq}) of the signal over the time interval τ. Thus, time weighting is really just a running average and a signal is predicted to becomes audible, if the running L_{eq} of the signal exceeds the hearing threshold at some point during the signal. The running average can be implemented by convolving the instantaneous signal power (p^2) with a kernel, w_t, and then convert back to amplitude (pressure) by taking the square root:

$$\bar{p} = \sqrt{p^2 * w_t} \tag{7}$$

where the symbol * denotes convolution, not multiplication.

w_t may be a simple rectangular function of unit energy and duration τ:

$$w_{t_{rectangular}} = \begin{Bmatrix} 0 \text{ for } t < 0 \\ \frac{1}{\tau} \text{ for } 0 \le t \le \tau \\ 0 \text{ for } t > \tau \end{Bmatrix} \tag{8}$$

or it may be a physiologically more realistic exponentially decaying kernel [3], also with unit energy and a time constant τ:

$$w_{t_{exponential}} = \begin{Bmatrix} 0 \text{ for } t < 0 \\ \frac{1}{\tau} e^{-\frac{t}{\tau}} \text{ for } t \geqslant 0 \end{Bmatrix} \tag{9}$$

3.1. Practical implementation of temporal weighting

To compute the running L_{eq} of a signal *sig*, with sample rate *fs*, the function Leqfast is called as:

```
Leq = Leqfast(sig,fs,tau,type)
```

where optional arguments *tau* and *type* specify the time constant (in seconds, default 0.125) and the shape of the weighting kernel ('r' is rectangular, 'e' is exponential (default)), respectively.

The rectangular kernel is created as:

*L = floor(fs*tau); %Time constant in samples*

w = [ones(L,1);zeros(length(sig)−L,1)];

Dividing by *tau*fs* normalizes the window to unit energy.

The corresponding exponential kernel is created as:

*w = exp(−(0:length(sig)−1)/(tau*fs))';*

As above, dividing by *tau*fs* normalizes the window to unit area.

As was the case with the frequency weighting, the convolution can be achieved by multiplication in the frequency domain and back-transformation to the time domain:

*Leq = sqrt((ifft(fft(sig.^2).*fft(w)))/L);*

3.2. Selection of tau

A remaining question is which value to select for the time constant. No definite answer can be given to this question, as the answer must come out of experimental evidence. However, the simplest solution is to use a single value and apply this value across all species and sound stimuli. The value of 125 ms was suggested by [8] because it is already an established standard in human audiometry (the so-called rms-fast weighting of sound level meters, see [18]) and provides a good average fit to data from harbor porpoises. Alternatively, one could use frequency-specific values for *tau* for the very few species where empirical data exist and for sounds with relatively narrow bandwidths. While this approach might provide a better fit between predictions and data for individual species, it would be at the cost of reduced transparency and comparability across studies and among species. Using frequency-dependent values for *tau* also adds further complications when evaluating broadband sounds, as there is no simple way to perform the running average with a frequency dependent time constant. The only solution would probably be to resolve the signal into frequency bands (one octave or one-third octave bands), convolve the output of each frequency band with a kernel that has a band-specific time constant, and then adding the results together in the time domain for the final output. The possible gain of such an elaborate procedure must be carefully weighed against the loss in simplicity and transparency. Thus, it is worth noting that everything else being equal, doubling the time constant (or halving it) corresponds to a change in L_{eq} of only 3 dB. The possible bias introduced by using a slightly too small or too large time constant should then be compared with other sources of uncertainty, which, in the case of field studies, are often considerably larger and likely to dominate.

4. Discussion of examples

Fig. 2 presents five different signals weighted first spectrally and then temporally, by means of the two functions described in Sections 3.1 and 4.1. The leftmost column shows the unweighted time signals. The second column shows the power density spectrum (Welch average, 512 point fft, Hann-window, 50% overlap). The third and fourth columns show the running time averages with a rectangular kernel and an exponentially decaying kernel, respectively. For all weighting results, black lines indicate the unweighted signal, blue lines indicate signals weighted with an LF-cetacean weighting (i.e. baleen whales), and red lines indicate signals weighted with an HF-cetacean function (porpoises and their like). Several important properties of the weighting functions are illustrated by these examples.

4.1. Broadband noise pulse

The unweighted signal has a flat frequency spectrum, which means that the frequency-weighted spectra closely mirror the weighting functions (compare to Fig. 1, and note that the frequency axis in Fig. 1 is logarithmic, whereas it is linear in Fig. 2). The LF-weighted signal drops off gently towards high frequencies, whereas the HF-weighted signal has a steep low-frequency cutoff. Running time averages show the differences between the rectangular and exponential windows. While the running average with the rectangular window follows the envelope of the unweighted signal fairly well, except for the rounded corners, the exponential kernel produces a long "tail" after the end of the unweighted signal. The weighted curves are also offset on the y-axis relative to the unweighted curve, which is a direct consequence of the removal of energy by the frequency weighting process.

4.2. Explosion

The frequency spectrum of the pulse has a very strong low-frequency emphasis, which causes a much lower amplitude of the HF-weighted signal than for the LF-weighted signal and L_{eq} of the LF-weighted signal is almost indistinguishable from the unweighted signal. Almost all energy is in the short primary pulse, which is more obvious in the weighting with the rectangular window. The separation between the primary pulse and the first echo is just above the time constant. Therefore, two distinct steps are formed by the running average. This is in sharp contrast to the exponential weighting, where the contribution of the echo is only visible as a small bump on the curve. In this case, the rectangular window provides a better representation of the transient nature of the sound, whereas the exponential weighting might give a better representation of the way the animal perceives the sound. Humans, and presumably mammals in general, do not perceive even powerful echoes as separate pulses if they arrive shortly after the main signal, which implies that the psychophysical observations are more consistent with the almost constant decay that characterizes the exponential kernel and is inconsistent with the step function resulting from the use of the rectangular kernel.

4.3. Echolocation clicks from bottlenose dolphin

The frequency weighting of a series of echolocation pulses from a bottlenose dolphin (*Tursiops* sp.), shows that the bulk of the energy is present at frequencies audible to HF-cetaceans (and also MF-cetaceans, as the two curves are only marginally different), but also that sufficient energy is present at low frequencies to make them audible to LF-cetaceans. The L_{eq} changes throughout the click train, tracing the changes in click amplitude, but also with contributions from individual clicks being rendered clearly visible. As shown for the explosion pulse, the rectangular kernel produces an abrupt output cut-off, which is not consistent with the perception of the pulse train. The overall development of L_{eq}, nevertheless, mimics the curves made with the exponential kernel.

4.4. Airgun pulse

The airgun pulse has an even stronger low-frequency emphasis than the explosion signal. Therefore, even the LF-cetacean weighting removes energy from the signal and the HF-weighted signal is about 60 dB lower than the unweighted signal. Nevertheless, because the source levels of airgun pulses are very high, the signal to noise ratio (signal above ambient noise) is so large that the pulse is still clearly visible in the L_{eq} of the HF-weighted signal. Noticeable is that the peak of the HF-weighted pulse occurs earlier than

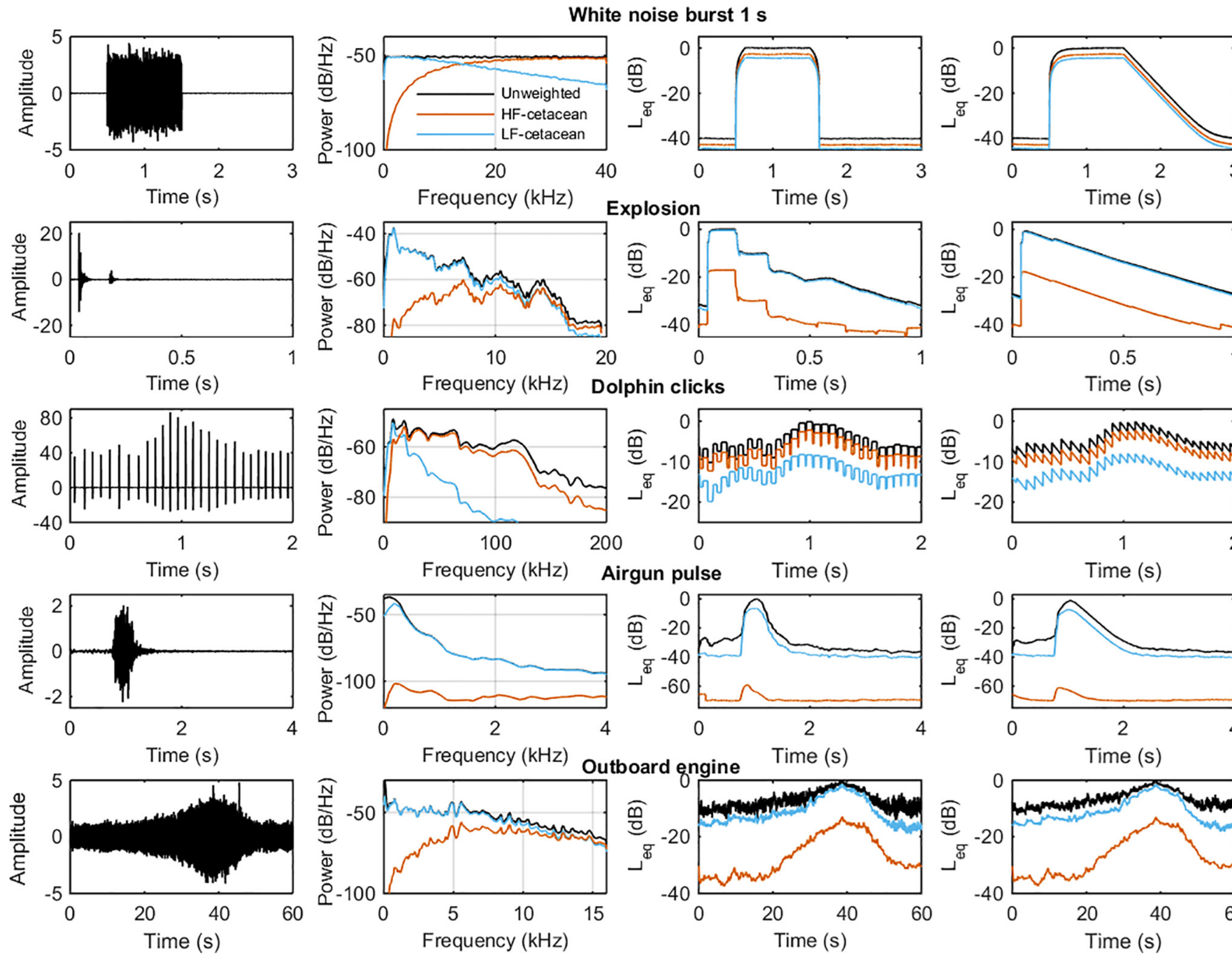

Fig. 2. Examples of frequency and time weighting for different signals. Columns left to right: unweighted time signal, power density spectrum (Welch average), L_{eq}, rectangular kernel of 125 ms, and L_{eq}, exponential kernel with τ = 125 ms. Black lines are unweighted in all plots, blue lines are LF-cetacean weighted and red lines are HF-cetacean weighted. Note, the axes differ among plots and that amplitudes have been normalized so that the maximum of L_{eq} of the unweighted signals equals 0 dB (on an arbitrary amplitude scale).

the peak of both the unweighted and the LF-weighted pulses. This phenomenon is not an artefact of processing, but is due to the higher sound speed of the high-frequency components of the pulse. Note also that the duration of the airgun pulse is so long that the difference between weighting with a rectangular and an exponential kernel becomes marginal.

4.5. Outboard engine

This signal is one minute long, which is considerably longer than the other signals that were analyzed. The recording contains the passage of a boat with an outboard motor (closest approach about 35 sec into the signal). The overall (average) frequency spectrum slopes towards higher frequencies, reminiscent of pink noise, in agreement with typical spectra of ambient noise in the ocean. This slope results in lower weighted levels for the HF-weighting, whereas the LF-weighted spectrum is closer to the unweighted levels. Because the signal duration is much longer than the time constant, the overall L_{eq} curves are very similar for the rectangular and exponential kernels. The exponential kernel, however, provides a higher degree of smoothing, as observed for the explosion and the dolphin clicks. Therefore, the fast fluctuations of the L_{eq} curve are smaller than for the rectangular kernel. While the maximum overall level of the LF-weighted signal (when the boat is closest to the recorder) is about 10 dB higher than the HF-weighted signal, the change in level as the boat passes is higher for the HF-weighted signal. Because ambient low-frequency noise dominates when the boat is far away, the LF-weighted signal only increases by about 10 dB as the boat passes, whereas the HF-weighted signal increases by about 20 dB during the passage.

4.6. Extracting a single value to represent loudness

One last step remains when applying weighting to the signals. The weighting functions return a running L_{eq}; however, to test for a possible correlation between loudness and behavioral reactions a single number is required, characterizing the loudness of the particular signal. This number should describe the loudest part of the signal. It is simplest to select the maximum of the running L_{eq}, shown in Table 2, for the five signals, shown in Fig. 2. It is immediately clear that the differences between the rectangular and exponential kernels are trivial, all being within 1 dB of each other. The overall maximum value is sensitive to random fluctuations and, for some applications, it might be preferable to use a slight smoothing (low-pass filtering) before finding the maximum. However, for all practical purposes, variation of 1 dB is well within measurement errors and, at least for the signals shown in Fig. 2, the choice of kernel does not influence the result.

Table 2
Peak L_{eq} for the five different signals in Fig. 2, for all combinations of frequency weighting and time weighting used. All signals were normalized prior to analysis to 0 dB for the unweighted, rectangular case.

Frequency weighting	Unweighted		LF-weighted		HF-weighted	
Kernel type	Rectangular	Exponential	Rectangular	Exponential	Rectangular	Exponential
White noise	0 dB	0 dB	−4 dB	−4 dB	−2 dB	−2 dB
Explosion	0 dB	−1 dB	0 dB	−1 dB	−16 dB	−17 dB
Dolphin clicks	0 dB	0 dB	−8 dB	−8 dB	−2 dB	−1 dB
Airgun pulse	0 dB	−1 dB	−6 dB	−7 dB	−59 dB	−60 dB
Outboard engine	0 dB	0 dB	−1 dB	−1 dB	−12 dB	−12 dB

Some of the differences between the frequency weighting functions discussed here are also evident in the peak L_{eq} values shown in Table 2. The L_{eq} of the signals with most energy at low frequencies (explosion, outboard engine, and, in particular, airgun pulse) is significantly lower for the HF-weighted signal, while the opposite is the case for the dolphin clicks. These differences relate to corresponding differences in the audibility of the signals to LF- and HF-cetaceans, respectively. However, several factors are at play, including the hearing threshold at the frequency of best hearing, as well as ambient noise. Thus, it does not follow immediately that the audibility of a signal for one species group is lower than the audibility for another species group just because the weighted L_{eq} is smaller. In general, weighted L_{eq} values should not be compared across species groups, but should only be compared to weighted thresholds for TTS and behavioral reactions. See [7] and [19] for examples and a discussion of this topic.

4.7. Processing large files

The examples shown in Fig. 2 are all very short signals, which makes it possible to process the entire signal as a whole. For some applications, one might want to compute running L_{eq} for very long recordings. Ultimately, the limiting factor for such processing is the memory of the processing computer, which determines the size of signals that may be stored and handled. However, processing time for the convolutions dramatically increases with increasing signal length, and quickly becomes the de facto limiting factor. Such longer signals should be cut into smaller segments, which are processed separately and combined afterwards. An example of a simple script for this approach is provided as Supplementary S1. This script cuts the longer signal into 50% overlapping segments, applies a Hann-window to each segment, before processing them with the frequency and time weighting functions, and then sums the output sequentially in the same order as the inputs. Supported file types are determined by the capabilities of the Matlab function audioread, which is currently limited to wav, au, flac, ogg, mp3, and mpeg4. Although the example function will process mp3 and mpeg4 files correctly, the use of these formats is strongly discouraged, as the lossy compression is very likely to induce spurious errors and artefacts into the signals. An optional downsampling of the output is recommended for long signals. A further increase in processing speed, beyond the scope of this presentation, could be achieved by other techniques, such as compiling the code or adapting parallel processing techniques.

5. Conclusion

It was conjectured in the introduction, that behavioral reaction thresholds to sound stimuli might be derived from appropriate time and frequency weighting of the sounds. This conjecture can only be tested against results from experiments, where reaction thresholds are derived by observation of the behavior of wild or captive animals, coupled to measures of the sound to which the animals are exposed. It is our hope and intention to facilitate testing (and by that possible falsification) of the conjectured correlation between weighted L_{eq} and behavioral reactions, by providing the practical tools to perform the weighting of the signals and, thus, perform the necessary correlations. Therefore, in conclusion, we encourage others to use these tools in future experiments (and possibly in re-analysis of existing data) and report the results.

5.1. Software availability

The functions described in this paper are supplied as supplementary online material, together with the sample signals used to generate Fig. 2. The functions are also available at GitHub (https://github.com/beedholm/loudness), which will allow for future updates, whenever new guidance regarding auditory weighting is published.

Declarations of interest

None.

Acknowledgements

Funding for this study was provided by the Danish Environmental Protection Agency (JT) and the Danish independent research fund for natural sciences (KB). Constructive comments from an anonymous reviewer is also acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2018.09.022.

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