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Anthony D. Hawkins, Craig Johnson, and Arthur N. Popper

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JASA ARTICLE

How to set sound exposure criteria for fishes[a)]

Anthony D. Hawkins,[1,b)] Craig Johnson,[2] and Arthur N. Popper[3,c)]
[1]*The Aquatic Noise Trust, Kincraig, Blairs, Aberdeen, AB12 5YT, United Kingdom*
[2]*Systematic Ecology, Bethesda, Maryland 20187, USA*
[3]*Department of Biology, University of Maryland, College Park, Maryland 20742, USA*

ABSTRACT:
Underwater sounds from human sources can have detrimental effects upon aquatic animals, including fishes. Thus, it is important to establish sound exposure criteria for fishes, setting out those levels of sound from different sources that have detrimental effects upon them, in order to support current and future protective regulations. This paper considers the gaps in information that must be resolved in order to establish reasonable sound exposure criteria for fishes. The vulnerability of fishes is affected by the characteristics of underwater sounds, which must be taken into account when evaluating effects. The effects that need to be considered include death and injuries, physiological effects, and changes in behavior. Strong emphasis in assessing the effects of sounds has been placed upon the hearing abilities of fishes. However, although hearing has to be taken into account, other actual effects also have to be considered. This paper considers the information gaps that must be filled for the development of future guidelines and criteria. https://doi.org/10.1121/10.0000907

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I. THE PURPOSE OF THIS PAPER

Each of the authors of this paper has, in various ways, been engaged with studying, thinking about, and assisting with regulatory activities associated with the potential effects of anthropogenic sound upon fishes for more than 20 years. Over this period, we have realized that there are still major gaps in information concerning the potential effects of sound on fishes. There are also major problems in the way that this topic has been considered and discussed. Indeed, we have been particularly "bothered" by the fact that many critically important words and ideas that are central to any discussion of the effects of anthropogenic sound on fishes are used in diverse ways by various investigators, regulators, and agencies. Indeed, one can almost analogize the diversity of use to that described for the Tower of Babel (Genesis 11:1-9), which emphasized the diversity of human languages. Thus, in discussing the effects of anthropogenic sounds, people often use the same words, but with very different meanings that are often not clear to others. This makes developing a common understanding of ideas, and seeking appropriate solutions, exceptionally challenging.

The other issue that we often encounter is that there is a broad lack of understanding of how to set rigorous sound exposure criteria for fishes, as well as a diversity of ideas about how this should be done. There have been many different and often incompatible approaches to collecting the data needed to develop such criteria. And, as a consequence, it is hard to use much of the current data in setting criteria. As a result, there is a strong potential for different criteria to be established for the same effects.

Therefore, the purpose of this paper is to provide a common foundation for developing sound exposure criteria for fishes for use by researchers, regulators, and other interested parties, but not to provide final answers. To lay that foundation, we recommend specific definitions for critical concepts and discuss how they should be used. We are not suggesting, however, that our recommendations end the discussion of these concepts. Instead, our goal is to get our colleagues in the research and regulatory communities around the world moving towards a dialogue that results in a common understanding. We invite discussion and debate, but we also assume that all interested in the effects of anthropogenic sound on fish share a common goal of preventing those effects from impacting the viability and resilience of fish populations.

II. OVERVIEW

There is increasing concern that underwater anthropogenic sound may have detrimental effects upon fishes (Hawkins and Popper, 2018). Potential adverse effects include death, injury (including loss of hearing), physiological stress, and changes in behavior. Behavioral responses are especially detrimental if fishes become more exposed to predators, are displaced from feeding or spawning grounds, have their migrations affected, or experience disruption of communication between individuals. Sound exposure criteria are sound levels, based on acoustic response thresholds, above which sounds may have adverse effects on specified animals.

[a)]This paper is part of a special issue on The Effects of Noise on Aquatic Life.
[b)]Electronic mail: a.hawkins@btconnect.com
[c)]ORCID: 0000-0002-0312-7125.

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One problem in establishing criteria for fishes, however, is that even though there are great concerns about the *potential* effects of anthropogenic sounds, there are major gaps in our knowledge of the *actual* effects that take place. Thus, there is a substantial need to examine the effects upon fishes of exposure to anthropogenic sound if we are to deal better with its control and mitigation. In particular, there is a lack of insight into the behavioral responses of free-ranging fishes to anthropogenic sounds, the consequences of such behavioral responses for individual fish, and the the impacts upon fish populations (Slabbekoorn *et al.*, 2019).

Indeed, until such gaps are filled, it will be very difficult to establish reasonable criteria that set out the levels of sound from different sources that could possibly adversely affect fishes (e.g., Popper *et al.*, 2014; Hawkins *et al.*, 2015; Hawkins and Popper, 2018; Popper and Hawkins, 2019). Moreover, criteria are needed to support regulations that protect living organisms and ecosystems from the potential adverse effects of noise. The term *noise* is used to describe sounds that may be unpleasant, loud or disruptive to hearing, and that may result in disturbance, or that can hinder detection of important signals and cues. The ultimate goal in developing criteria is to identify those levels of sound that may result in adverse biological or ecological effects, based on data collected during empirical studies, and which can provide the basis for developing regulations that avoid those impacts.

Setting criteria for fishes is quite different to setting them for marine mammals—another group for which there are great concerns about anthropogenic sound. Indeed, while there is a growing body of literature available to support the development of anthropogenic sound criteria for the alterations of auditory thresholds in marine mammals (e.g., Southall *et al.*, 2007; NMFS, 2018; Southall *et al.*, 2019), the data necessary to support criteria for fishes are still largely lacking.

Investigations into the effects of acoustic exposures on marine mammals initially focused on hearing then expanded to include a broader array of physical, physiological, and behavioral responses. It is now evident that alterations to auditory thresholds are not the only responses of concern for fishes. Initial attempts have been made to recommend criteria for fishes for a wider range of responses, using the results of scientific studies whose designs and sample sizes support valid inferences about the effects of sound upon the organisms studied (Valentine, 2009; Popper *et al.*, 2014; Popper *et al.*, 2019a). Those results were based on detailed experiments carried out under appropriate conditions. However, setting criteria for most fishes has been problematic because they are not only exposed to the same sources of sound that affect marine mammals, they are also exposed to a wider variety of potentially harmful sounds in different environments and circumstances. And, adding to the complexity of the problem, fishes are more diverse than marine mammals, with over 33 000 species of fish compared with about 130 species of marine mammals (Bass and Ladich, 2008). Moreover, many fish species are important to the human and marine mammal food chains, and for the health and stability of the marine environment.

Beyond the lack of data with regard to potential effects of anthropogenic sound on fishes, there are many major issues in terms of research design and research questions that must be resolved to ensure that the data are produced by studies that are relevant, credible, allow robust inferences about study subjects, and produce results that be applied more broadly (see Valentine, 2009; Popper *et al.*, 2019b). These issues include:

- The definition of terms that are used in very different ways by different authors, in regulations, policies, and guidance (words such as: effect, impact, onset, noise, etc.).
- The selection of species for research.
- The acoustic conditions within the environments in which fishes are studied.
- Whether data on behavior from fishes studied in enclosures can provide insight into how fishes will react to sounds in the wild.

Thus, the aim of this paper is to discuss ways of establishing sound exposure criteria for fishes. Specifically, we discuss a number of issues that such criteria for fishes should address and then how to study the effects of sound on fishes (Sec. VI). We then comment on current sound exposure criteria for fishes (Sec. VII) and conclude (Sec. VIII) with recommendations on how the gaps in our knowledge can be filled in ways that support the development of future criteria. However, before getting to these issues, it is important to first discuss the current regulatory environment (Sec. III), and then to define a number of terms and ideas (Sec. IV).

We want to make it clear that our goal is not to develop new criteria *per se*. Instead, we point out that two authors of this paper have been arguing strongly that the interim criteria proposed by Popper *et al.* (2014) should now be adopted until more data become available to update them (Popper and Hawkins, 2019; Popper *et al.*, 2019a). Similar recommendations for use of these interim criteria have been made by others (e.g., Andersson *et al.*, 2017; Faulkner *et al.*, 2018).

III. SETTING REGULATIONS

A report on anthropogenic underwater noise was submitted to the Assembly of the United Nations (UN), and to those States party to the United Nations Convention on the Law of the Sea (UNEP, 2017). Based on this report, the issue of whether noise pollution should be included in the Convention on the Law of the Sea is now being considered by UN Member States. If it is included, then Member States will be required to take all the measures necessary to prevent, reduce, and control noise pollution of the marine environment. Laws and regulations of Member State will then have to take into account any internationally agreed rules, standards, and recommended practices and procedures.

Most of the regulatory frameworks associated with anthropogenic sound have focused on marine mammals, and often the ideas and language used do not fit fishes (or, for that matter, aquatic invertebrates and reptiles). Thus, the following discussion mentions marine mammals but makes the point that many similar issues need to be considered for fishes and other aquatic animals as well. However, there are additional issues that need to be considered for fishes (and invertebrates), such as particle motion and species diversity, that go beyond the issues for marine mammals.

In many countries, the law requires assessments of sound-producing activities that may have an impact on animals in the aquatic environment. In addition to preparing environmental impact assessments (EIAs) for proposed developments, there is also a need to consider mitigation measures and/or restrictions upon those activities that may generate underwater sounds. The EIA is the main tool utilized by regulatory agencies to ensure that the environment and the living organisms it supports are adequately protected. Proposals for various projects may be rejected on the basis that they involve major risks to the environment and its living resources, or the proposals may be modified where some risk is considered acceptable, or where mitigation of the effects might be possible.

EIAs [sometimes termed environmental assessments (EAs) or environmental impact statements (EISs) in the US] are wholly dependent upon the information available to enable risks to be evaluated. Therefore, some kind of risk-assessment procedure is needed to assess the impact of noise on aquatic life, utilizing any knowledge available to enable the levels of risk to be assessed and any information gaps identified. Rational decisions can then be taken on any development proposals that may put animals at risk.

As part of the process of risk-assessment, it is necessary to identify those levels of sound that cause particular effects from different types of sources with the ultimate goal of providing sound exposure criteria. Such "criteria" indicate the levels of sound, in specified metrics, that must not be exceeded by anthropogenic sound producing activities, in order to prevent potential adverse effects. The effects themselves must be measurable quantitatively and must have high biological relevance. Determination of the biological relevance of particular effects is especially important. The criteria can then be used by governments to establish regulations, policies, and guidance that specify those sound levels that are acceptable and those which should not be exceeded.

In the United States, the US Marine Mammal Protection Act (16 U.S.C. 1361 *et seq.*; MMPA), with its prohibition against "take" of marine mammals, as well as its permitting requirements, has provided the initial foundation for how one thinks about, assesses, regulates, and mitigates sound exposure. However, the MMPA and its prohibitions and permitting requirements do not apply when considering any taxa other than marine mammals.

Instead, for fishes, statutes such as the US National Environmental Policy Act (42 U.S.C. 431 *et seq.*; NEPA[1]; and the US Endangered Species Act of 1973 (16 U.S.C. 1531 *et seq.*; ESA[2]) have provided the primary legal foundation for how to think about, assess, regulate, and mitigate the effects of sound on fishes.

In some cases, this legal foundation has led to outcomes for fish that are different from outcomes developed for marine mammals. For example, while assessments associated with the MMPA have primarily focused on estimating the potential number of acoustic exposures, the ESA and NEPA also require an explicit evaluation of the probable consequences of those exposures on the individuals and populations exposed. The latter two statutes also require regulators to consider the magnitude of an effect, not just whether an animal has been exposed to potentially harmful sound. To satisfy these statutes, sound exposure criteria for fishes must recognize the variety of consequences of acoustic exposures and that some acoustic exposures pose greater risks to fishes than others. Moreover, it is important to develop acoustic criteria for all "groups" of fishes (defined as in Table II), and particularly fishes that use sound to communicate or locate prey, species that mature late and have low fecundity such as elasmobranchs and sturgeon, commercially-important species, as well as imperiled fish species (Normandeau, 2012).

Canada's Species at Risk Act and the US ESA contain similar provisions: among other things, they both prohibit killing, harming, and harassing endangered or threatened species, where "harm" represent effects that reduce the fitness of individuals while "harass" represents effects that disturb, alarm, or molest individuals or populations (Thériault and Moors-Murphy, 2015). Similar approaches are not taken in other countries. However, in Europe, the EU Habitats Directive of 1992[3] requires Member States to ensure the physical protection of individual animals across all the EU countries, as well as the conservation of breeding and resting sites for certain particularly rare and threatened species within a network of protected sites. Natura 2000[4] is the network of protected areas, covering Europe's most valuable and threatened species and habitats. Protected species are listed in Annex IV of the Habitats Directive. Article 12(1)(b) of the Directive prohibits the deliberate *disturbance* of Annex IV species especially during periods of breeding, rearing, hibernation, and migration. Under EU directives and U.S. law, special measures must also be taken to avoid the deterioration of habitats or disturbance of species under Article 6(2). Again, it is important to establish criteria that are related to the disturbance of all fishes.

A number of other countries are concerned about the impact of anthropogenic sounds upon marine wildlife (Erbe, 2013). Some of these countries require EIAs that address acoustic impacts on marine mammals (Erbe, 2013), but have not developed their own sound exposure criteria for fishes.

IV. DEFINITION OF TERMS

In order to set criteria, it is important that investigators, regulators, industry, and other interested parties all "speak the same language" with regard to the use of acoustic terms that are relevant to regulatory processes. Thus, before continuing, we find it necessary to first define a number of terms because they are widely found in the literature. We also do this since we have found that different authors provide many of these terms with different meanings or use the words without explaining their meaning, leading to confusion in the literature as to what is actually meant.

Because the terms are critical for any analysis of potential effects on fishes, they ultimately require an agreed set of definitions. We offer definitions here that relate to discussions of criteria and guidelines. At the same time, we realize that our definitions are not going to be agreed to by all those concerned with anthropogenic sound and fishes. Essentially, the definitions relate to the terms used in this paper. More importantly, our goal here is to point out that there are discrepancies in the use of these, and many other terms, that must be sorted out at some point in the future.

Biologically significant: as used here this term refers to an effect (or "impact") or a change whose direction, magnitude, and/or duration is sufficient to have consequences for the fitness of individual fish or fish populations (Steidl *et al.*, 1997; Johnson, 1999; Nakagawa and Cuthill, 2007). The biological significance of an effect is unrelated to its statistical significance.

Criterion (plural *criteria*): a numerical principle or standard by which something may be judged or decided. Sound exposure criteria are sound levels, based on acoustic response thresholds, above which sound levels may have adverse effects on specified animals.

Disturbance: any discrete event that has adverse effects upon individual animals, ecosystems, communities, or population structures, and changes resources, patterns of habitat use, or the physical, chemical, or biotic environment.

Effect: a change caused by sound exposure that is a departure from a prior state, condition, or situation, which is called the "baseline" condition (see World Health Organization document, IPCS, 2004). It is important to note that effects are not necessarily deleterious—effects can be positive or negative (but see *impact*). For the purposes of assessing acoustic exposures or setting criteria, it is important to recognize that an effect has a direction (positive or negative), magnitude (the degree of departure), and duration, and is often associated with a recovery curve.

Exposure: contact or co-occurrence between a stressor and a receptor (EPA, 1998). As applied in this paper, "acoustic exposure" consists of organisms or habitat features that occur in a sound field, and includes a description of the spectral qualities of the sound, the received level, how long the organism or habitat is exposed to the sound field, and the circumstances of the occurrence.

Changes in *Fitness*: the expected contribution of an individual, allele, genotype, or phenotype to future generations of a population. It can, for example, relate to specific traits that make one individual more successful than others within a population. We focus, however, on the two primary demographic components of fitness as points of reference for individual-level effects: (1) a change in the probability of individuals surviving to adulthood and (2) a change in their expected mean or median lifetime reproductive output. Changes in one or both of these components of fitness determine whether an effect is likely to be biologically significant for individual organisms. Exposure to sounds can affect both the overall reproductive output (success) of a population, as well as the fitness advantage of certain animal activities, such as sound production.

Guidelines[5]: advice relating to the determination and application of sound exposure criteria based on a critical review of the data available on the potential effects of sound exposure.

Harass: for imperiled freshwater anadromous and coastal fishes this has been defined as "an intentional or negligent act or omission which creates the likelihood of injury to wildlife by annoying it to such an extent as to significantly disrupt normal behavioral patterns which include, but are not limited to, breeding, feeding or sheltering" (50 CFR 17.3). There is no comparable legal definition that applies to the endangered or threatened marine fishes and coastal or anadromous fishes administered by NOAA or by the European Commission.

Impact: a biologically significant (see Sec. IV) effect (see definition) that reflects a change whose direction, magnitude and/or duration is sufficient to have consequences for the fitness of individual fish or populations of fishes.

Injury: this term has not been defined for fishes in the US or EU (although the term has been defined for marine mammals). We use the term to refer to any tissue damage and analogous physiological effects resulting from an acoustic exposure involving an anthropogenic source. As such, injury can range from scale loss to impacts that result in massive tissue damage that may lead to death.

Onset: in the US, the term onset and the phrase *onset of effect* are widely used in regulations and in the literature to denote the point at which a regulation or guideline may come into play. While acoustic guidelines for marine mammals define a change in threshold of 6 dB as the onset of a temporary loss of hearing sensitivity [Temporary Threshold Shift (TTS); see NMFS, 2018], no clear definition of onset of any acoustic or other effect has been identified for fishes. In fact, the term is used in very different ways by different investigators and in different documents. Thus, in the US, the word onset may be used as the start of an effect on an individual animal or on a population. Additionally, onset may be used as the very first start of an effect, such as a fin movement or a momentary startle response, or it may be used to indicate the point when an effect starts to change fitness.

Salience, saliency: is the quality of a cue, signal, or other change in an organism's environment that, from the perspective of an organism: (a) is distinguishable from other similar cues, signals, or stimuli; (b) activates relevant receptors in one or more physical, physiological, or neural (or cognitive) pathway; and (c) is sufficiently strong or coherent to trigger or elicit a physical, physiological, behavioral, social/ecological, or demographic response (see Kayser *et al.*, 2005; Knudsen, 2007).

Susceptibility: for the purposes of assessing the effects of noise on fish, this refers to factors intrinsic to individuals (e.g., their physical, developmental, and physiological state and behavior) that make them prone (or more prone) to adverse outcomes given exposure to sound-related phenomena (Suter and Glen, 1993; Parkin and Balbus, 2000).

Threshold: this term is used to describe a sound (or other stimuli) level that must be exceeded for a physical, physiological, or behavioral reaction or response to occur. One approach to determining such a threshold relies on the development of *exposure-response* relationships. We also note that the same term can be used for other sources of anthropogenic pollution such as light, chemicals, etc.

Vulnerability: refers to the combination of the intrinsic factors associated with an organism's susceptibility, factors related to exposure (duration, timing, frequency, intensity, etc., of sound exposure) and relevant co-factors in the individual's environment (see Parkin and Balbus, 2000).

V. ISSUES TO ADDRESS IN DEVELOPING CRITERIA

Sections V A–V E discuss the various issues that must be taken into consideration in developing anthropogenic sound criteria for fishes. We recognize that there may be other issues as well, but these are, in the view of the authors, the ones of primary concern.

A. Attributes of sound

In developing criteria for exposure to anthropogenic sounds, and in producing more robust assessments that support those criteria (e.g, Popper *et al.*, 2019b), it is imperative to recognize the various factors that determine the susceptibility and vulnerability of fish to excessive sound. These factors include attributes of the sound itself, such as how sound propagates and its acoustic characteristics (e.g., frequency), and also includes some attributes that are less likely to be important for marine mammals (e.g., particle motion).

The following list of factors is provisional at this stage and requires further discussion. However, the relevant factors are included.

1. Sound propagation

It is often commonplace for regulatory authorities to ask for information on the distances that sounds will travel from the source, and even to regulate sound generation by specifying distances beyond which a sound must not exceed a particular level, to avoid harmful outcomes. As an example, in US waters, measurements are often focused on identifying or validating ranges at which the impact criteria for key fish species are reached. These particular sound exposure criteria are used by NOAA for fish species under its jurisdiction. Such criteria rely on adequate modelling of sound propagation from the source. In midwater in the open sea, under conditions where the topography and any changes in temperature and salinity have been measured, it is possible to model the propagation of sound and to estimate the magnitudes of sound pressure and particle velocity at different distances, using the wave equations. However, under some circumstances, such as in very shallow water (e.g., where the water depth is less than the sound wavelength), or where the sources or receiving animals are close to the surface or the substrate, it can be more difficult to model sound propagation (e.g., Lumsdon *et al.*, 2018; Prior *et al.*, 2019). Moreover, it is hard to model sound propagation from large and complex sources such as ships, pile drivers, and seismic airgun arrays. As a consequence of all of these variables, it is not always possible to specify sound exposure criteria in terms of effective distances because of the complexity of sound transmission in the actual aquatic environments occupied by animals.

2. The type of sound

a. Sound pressure vs particle motion. Sounds are most often described in terms of the changes in sound pressure. However, it has been established experimentally that many fishes respond to the particle motion (reviewed by Hawkins, 2014). Particle motion is the back and forth motion of the component particles of the medium, measured as the particle displacement, velocity, or acceleration. Some fish species also respond to sound pressure as well as particle motion (e.g., Popper and Hawkins, 2018; Popper and Hawkins, 2019). It has suggested that whales could potentially use particle motion to determine the distance of signaling animals (Mooney *et al.*, 2016).

Distant from a source, at a depth far from reflecting boundaries (e.g., surface, bottom), particle motion is proportional to the sound pressure. However, close to the sound source, in the so-called *near field*, the magnitude of the particle motion is higher for a given sound pressure (e.g., Harris and van Bergeijk, 1962; van Bergeijk, 1964). Moreover, close to a boundary with a "soft" material, having low acoustic impedance, like air, the local amplitude of particle velocity may be much higher. Close to a "hard" boundary, like the seabed, the amplitude of particle velocity may be reduced. Some sound sources may, however, generate sound within the solid substrate, and this may result in interface waves travelling along the substrate surface (Hazelwood and Macey, 2016), with quite high levels of particle motion at the low frequencies to which fishes are sensitive.

B. Types of sounds

Assessments of the potential impacts of sound exposures typically distinguish between continuous sounds and intermittent sounds (sounds that stop and start, often repeatedly). They also deal with impulsive sounds that last for a short period of time and often have a wide bandwidth of frequencies. Assessments also consider the intensity of the sound (both sound pressure and particle motion) at the moment of exposure (the "received level" in dB), duration of individual exposure events, total duration of the acoustic exposure (that is, an integration of all exposure events), exposure frequency (number of exposure events in a given time interval), and the time interval between repeated exposure events (or "duty cycle"). However, assessments rarely consider attributes such as the timbre (the harmonic content of a sound); the roughness (rapid and often irregular amplitude modulation of a sound); and the fluctuation strength (slower amplitude modulation of a sound). These can influence how animals perceive sounds.

Because different kinds of sound have different attributes, they may have very different effects on animals, and this could result in criteria having to be developed for many types of sound. However, doing so would be very complex and time-consuming, and so it may be advantageous, and possible, to aggregate some sound types, such as the sounds measured at some distance from the source that are produced by seismic air guns or pile drivers. In considering the need to make it easier and faster to develop useful criteria, Popper *et al.* (2014) suggested that a noise classification system be developed, and each type treated separately for the purpose of impact assessment and risk analysis. A tentative classification of sources from these 2014 Guidelines was:

- Explosions—single or multiple events
- Seismic Airguns
- Pile driving
- Low and mid frequency active sonars
- High frequency active sonars
- Continuous sound sources, including shipping, dredging and drilling

Within each of these categories there may be some particular features to which fishes may be more susceptible. For example, when exposed to continuous sounds, fishes may be more susceptible to sounds with more complex temporal characteristics (as described later) rather than sounds without such complex characteristics. With impulsive sources, the rise time may be important in determining susceptibility. It may be possible to score these features for their influence upon susceptibility.

C. Attributes of the exposure

Exposure is defined as contact or co-occurrence between a stressor and a receptor (EPA, 1998). It may include the process and circumstances by which a sound or other stimulus comes into contact with an organism. Sound criteria focus on sound exposure levels (SELs) that must not be exceeded by sound-producing activities because of their potential adverse effects on living organisms.

In some cases, such as for marine mammals (Southall *et al.*, 2007; Southall *et al.*, 2019) and for fishes (Nedwell *et al.*, 2007), the sound levels may be "weighted." That is, they are matched to the hearing abilities of particular animals by filtering the sound using weighting curves that represent the sensitivity of an animal to different frequencies. These curves are determined by the measurement of hearing thresholds, which are the sound levels below which an animal is unable to detect a sound at different frequencies.

However, valid scientifically based weighting curves are lacking for most fishes. Within the UK, there has been some utilization of weighted criteria for fishes, as suggested by Nedwell *et al.* (2007). However, the validity of these weighted criteria has been strongly questioned and criticized (Popper *et al.*, 2014; Hawkins and Popper, 2016). This is because such weighting curves for fishes have often been developed using hearing thresholds derived from experiments conducted under poor acoustic conditions, or have used inappropriate measurements of the actual sound levels, especially for those fishes that are sensitive to particle motion rather than sound pressure (Popper and Hawkins, 2018). To obtain weighting curves for particular fish species, it is necessary to establish whether they respond to sound pressure or particle motion, and then to derive hearing thresholds at different frequencies under appropriate acoustic conditions.

Sounds at different levels and with differing characteristics can have different effects on fishes (reviewed by Popper *et al.*, 2014). While it is possible to suggest a wide range of potential effects, trying to develop criteria for every possible scenario (and for so many fish species and to a wide range of stimuli) is very difficult. In order to manage this diversity of potential effects Popper *et al.* (2014) developed a set of broad categories for potential effects that are quite similar to those used for other species (see Table I).

At the same time, there is a wide range of potential effects even within some of these categories. Moreover, the effects are generally not going to be "yes or no" response. Rather, in some cases, for example in relation to behavioral responses, there are likely to be exposure-response curves or functions (e.g., dose-response curves), relating the severity or probability of a response at different sound levels.

D. Sensitivity of fishes to sound

In developing sound exposure criteria, it has generally been assumed that the effects of sounds depend upon the hearing sensitivity and frequency ranges of animals. Thus, Southall *et al.* (2007) provided sound exposure criteria for cetaceans by dividing them into three groups, low-frequency, mid-frequency, and high-frequency) cetaceans (see also Southall *et al.*, 2019). In the latest provisional guidance on sound exposure criteria (NMFS, 2018), marine

TABLE I. Major effects of sound on fishes (based on Popper *et al.*, 2014).

The main effects to be considered are:
• Death, including instantaneous or delayed mortality.
• Injuries, that impair the function of some parts of the body.
• Permanent Threshold Shift (PTS), a loss of hearing ability from which the animal does not appear to recover or only recovers partially.
• Physiological effects, often measured as increased levels of stress hormones.
• Temporary Threshold Shift (TTS), a loss of hearing ability from which the animal appears to recover.
• Changes in behavior.
• Masking, affecting the ability of the animal to detect of biologically significant sounds.
• No obvious observed response.

mammals are divided into similar functional hearing groups (low-, mid-, and high-frequency cetaceans, and otariid and phocid pinnipeds).

Similarly, to date, most emphasis in assessing the effects of sounds upon fishes has been placed upon their hearing abilities. Initially, this was based on some authors grouping fishes as either specialists or generalists, depending on their hearing sensitivities and frequency range. It is now accepted that this was an over-simplification (Popper and Fay, 2011). Later, Popper *et al.* (2014) suggested sound exposure guidelines for broad groups of fishes, defined by the way they detect sound (Table II).

For the purpose of our current analysis, we group fishes based on their potential responsiveness to sounds, including anthropogenic sounds, with particular focus on the potential hearing capabilities associated with the relationship of the inner ear to the swim bladder. This differentiation between species is somewhat modified from the 2014 Guidelines in terms of groupings and focuses only on effects on hearing and related issues such as masking and temporary hearing loss (TTS). We suggest that having four groups, as opposed to the three in the 2014 Guidelines, may be more useful in setting criteria. The difference between this analysis and that of the 2014 Guidelines is that we have divided the Guideline category of fishes that involved the swim bladder in hearing into two groups (3 and 4 in Table II) to better reflect recent thinking about hearing capabilities and the involvement of the swim bladder. The hearing characteristics of fishes have recently been reviewed by Popper *et al.* (2019b).

However, sensitivity to sound *per se* may be over-rated as the key factor, as the levels of sound that actually affect fish behavior are well above hearing thresholds. For example, Hawkins *et al.* (2014) showed that mackerel (*Scomber scombrus*) responded behaviorally to similar levels of impulsive noise as sprats (*Sprattus sprattus*), although the sprats have especially low hearing thresholds as a result of gas-filled bullae associated with the ear, while the mackerel is sensitive only to particle motion. The point is that the sounds that affect behavior may well be well above the hearing thresholds that are determined for different species, and it may not be completely valid to assume that those with lower auditory thresholds (sensitivity to lower sound levels) will necessarily react more strongly to sounds presented at a very high level, well above those thresholds. Although the hearing abilities of fishes are not always the singly most important factors to be considered in evaluating susceptibility to sound exposure, they sometimes have to be taken into account, and perhaps considered alongside other key sensitivity factors.

Indeed, while there have been few studies that have examined fish hearing capabilities beyond sensitivity, it is possible that other sound characteristics are more important to hearing and the resultant behavior than sound level, and any disruption of these capabilities may have an impact on fishes. For example, it has been shown that fishes can discriminate between sounds that differ in intensity (Jacobs and Tavolga, 1967; Fay, 1985; Yan and Popper, 1993) and frequency (Jacobs and Tavolga, 1968; Fay, 1989). There is also evidence that fishes perform a wide range of other auditory distinctions (reviewed in Fay, 1980, 1988a; Fay and Megela Simmons, 1999) including temporal discrimination (Fay and Passow, 1982), determination of signal duration (Fay and Coombs, 1992), discrimination of complex signals (Fay, 1998b), and stream segregation (Fay, 1998a)—the perceptual grouping of sounds—a capability required in soundscape analysis (Fay, 2009).

However, while these studies demonstrate the ability of fishes to do complex sound processing, it must be kept in mind that, to date, most of these studies have been done on only a single species, the goldfish (*Carassius auratus*), a member of a teleost taxa, Otophysi, that have a broad hearing range and excellent hearing sensitivity (Group 4 in Table II), and which are primarily freshwater (other otophysan species include catfishes and zebrafish, *Danio rerio*). It will be imperative to replicate at least some of these studies in at least a few other species in Groups 1, 2, and 3 that do not have the "specializations" for hearing found in the otophysans, in order to be certain that these are characteristics of the hearing of all fishes, as well as goldfish.

E. Responses of fishes to sounds

Not all exposures to anthropogenic sounds will cause adverse outcomes for fish, so sound exposure criteria must be informed by how fish respond to acoustic exposures. One of the first questions the criteria need to address is whether

TABLE II. Groupings of fishes based on presumed hearing characteristics.

Group	Hearing characteristics	Examples
1	Fishes that do not possess a swim bladder, showing poor hearing abilities, and only have sensitivity to particle motion.	Sharks, mackerel, flatfish
2	Fishes with a swim bladder that is distant from the ear and does not contribute to sound pressure reception. These fishes are primarily particle motion detectors.	Salmon, Tuna, probably the majority of teleosts
3	Fishes where the swim bladder is close to the ear (but with no specialized physical connection), augmenting hearing sensitivity at some frequencies through the detection of sound pressure.	Atlantic cod, American and European eels
4	Fishes where the swim bladder or other gas volume is connected to the ear, enabling sound pressure to be detected, widening the frequency range of hearing and increasing hearing sensitivity to the extent that some species can detect sounds above 2 or 3 kHz, and some can even detect ultrasonic frequencies.	Herrings and relatives, otophysans (goldfish, catfish, etc.), some squirrelfishes, etc.

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an anthropogenic sound is likely to be salient in the prevailing circumstances. Although salience considers the audibility of sound, it also considers whether an animal is likely to pay attention to a sound in particular circumstances. For example, an anthropogenic sound may be detectable to fish that have taken refuge from a predator, but the sound might not be salient to the fish because all of their attention is directed toward the predator, so they are effectively unaware of the sound. Put in other, less formal, terms, the response of a fish (as all animals) partially depends on its motivation in the moment that a sound exposure occurs.

As a consequence, a simple received SPL exposure-response approach is not likely to be sufficient to predict the probability of a behavioral response. The exposure metrics need to take account of sound propagation, the hearing sensitivity of the receiver to different frequencies, the background noise levels in the environment, and the exposure in terms of the temporal characteristics of the noise. It is also important to recognise that fishes may react differently under different circumstances. For example, Hawkins *et al.* (2014) showed that sprats reacted quite differently to impulsive sounds by day and by night. There might also be seasonal differences in responsiveness, often related to the development and reproductive cycles of the fishes.

F. Significance of sound exposure to fishes

Sound exposure criteria for fishes should not only consider the responses of animals to sounds, but they should also consider the biological *significance* of those responses to the animals, rather than just the statistical significance (see Sec. IV). In other words, sound exposure criteria for fishes should focus on the biological significance of sound exposures.

Sound criteria organized around biological significance would first ask if exposing individuals to sound is likely to: (a) represent a significant adverse experience in the life of those individuals; (b) result in those potential stressors being likely to cause the individuals to experience significant physical, chemical, or biological responses; and (c) result in any physical, chemical, or biological responses that are likely to have biologically significant consequences for the fitness of the individual animal.

Criteria should identify SELs where the answer to these questions is "yes"; that is, sound exposure criteria should identify when sound exposure can be expected to result in biologically significant consequences that are adverse for individual fish or fish populations. The effects of exposure to underwater sound on fishes with respect to impact on key life functions, vital rates, and population parameters have been reviewed by Slabbekoorn *et al.* (2019) and by Hawkins and Popper (e.g., Hawkins and Popper, 2016; Popper and Hawkins, 2019).

As discussed in Sec. IV, the word *effect* generally refers to a change caused by an agent in a system, where the change is any departure from a prior state, condition, or situation used as a reference, where the prior state or condition is called the *baseline* (or *baseline condition*). Although not identified in most definitions, changes will have a *direction* (increasing or decreasing, positive or negative), *magnitude* (the size of the departure from a prior state or condition or size of the effect) and *duration* (how long does the change persist).

These three components—direction, magnitude, and duration—determine the significance of an effect and would determine the significance of an exposure to sound. A biologically significant effect (or *impact*) would consist of a change whose direction, magnitude, or duration is sufficient to have consequences for one or more components of the fitness of individual fish or populations of fishes. Sound exposure criteria should make it possible to distinguish between sound exposures that can be expected to be biologically significant and those that are not. Although Table I lists several "effects," only one of them (death) can be explicitly linked to biological significance; criteria that apply to the other effects in Table I need a similar, explicit link (this is discussed further in information gaps).

In most regulatory settings, relevant consequences will extend beyond the exposed individuals to populations, species, ecological communities, and ecosystems. To the degree that data allow, noise criteria should signal when acoustic exposures have consequences that can be expected to extend beyond the level of individuals. To bridge the gap between observed effects on individual fish and impacts on populations, investigators have attempted to develop models that explicitly link sound exposures from the exposed individuals to populations and then to ecosystems. For example, the Population Consequences of Acoustic Disturbance (PCAD) approach and its variants, including the Population Consequences of Disturbance (PCoD) (National Research Council, 2005; Booth *et al.*, 2014; King *et al.*, 2015; Sivle *et al.*, 2015; Slabbekoorn *et al.*, 2019) explicitly link individual-level effects to marine mammal populations and population-level effects upon ecosystems. Hawkins and Popper (2016) examined alternatives to these PCAD/PCoD approaches and Rossington *et al.* (2013) developed an individual based model to predict the impacts on Atlantic cod from sounds generated during a pile-driving event at an offshore wind farm in Liverpool Bay, UK.

These various assessment approaches would support the development of robust sound exposure criteria. However, these approaches are also limited by the limited availability of evidence that links sound exposures to the fitness of individual fish and the subsequent impact upon fish populations. The theoretical foundations necessary to link behavioral changes to changes in individual fitness, "canonical cost" ("canonical cost"; McNamara and Houston, 1986; Mangel and Clark, 1988; Gill and Sutherland, 2000; Christiansen and Lusseau, 2015), and assessments based on energetics (Anderson, 2000; Anderson *et al.*, 2008; Kooijman and Kooijman, 2010) have been developed, but they are not operational. As a result, we are poorly equipped to do more than use expert judgment for predicting non-lethal consequences of noise exposures. Usually, decisions are based on assumptions about effects of behavioral changes upon the population dynamics of a single species. This constrains our ability to recognize impacts when they occur, it constrains the rigour of our impact assessments, and it prevents us from developing criteria that could be used to prevent these outcomes.

G. Monitoring and measuring underwater sounds

In monitoring the actual sound to which a fish is exposed, it is important to recognize that all fish and invertebrates detect the particle motion of the sound field, while only a portion of bony fishes (and no elasmobranchs) also respond to sound pressure (e.g., Nedelec *et al.*, 2016; Popper and Hawkins, 2018).

Measuring or estimating the sound fields to which animals are exposed poses formidable difficulties. While it is easy to measure sound pressure using commonly available hydrophones, measurement of particle motion is more difficult, and fewer instruments have been developed to measure particle motion. Thus, it has become commonplace to estimate the particle velocity from measurements of the sound pressure, using either the plane wave equation or the spherical wave equation. Such estimates are only valid under well-specified circumstances, distant from reflecting boundaries (see Hawkins, 2014; Nedelec *et al.*, 2016). Such conditions do not prevail in small laboratory aquarium tanks, in shallow water, or close to the sea surface or seabed (e.g., Rogers and Cox, 1988; Duncan *et al.*, 2016; Rogers *et al.*, 2016; Campbell, 2019). Where animals respond to particle motion, rather than sound pressure, it is important to specify the actual particle motion levels, in terms of the particle displacement, particle velocity or particle acceleration.

Current regulatory activities focus on sound pressure since it is more easily measured. However, criteria based on sound pressure suffer from their not being based on the signal that most fishes detect. Thus, saying that fishes show behavioral responses starting at a sound pressure of 150 dB is rather meaningless, since some fishes (e.g., those in Group 1 and Group 2 of Table II) do not respond at all to sound pressure. There is also the problem that we know very little about particle motion detection thresholds for most fishes (e.g., Nedelec *et al.*, 2016; Popper and Hawkins, 2018), and so even if we were to measure particle motion in an environment, we are still not in a position to provide regulatory guidance based on that information. Moreover, as the inner ears of all fishes are sensitive to particle motion, there is the possibility that very high levels of particle motion may cause damage to the ears by shaking them.

Underwater sounds may be divided into continuous and impulsive signals. Continuous sounds can be tonal or broadband, and some may start and stop. Transient or impulsive sounds may be expressed in terms of their peak levels. Definitions of a number of relevant terms are given in Table III.

It is important to note that the most often encountered terms, root-mean-square (rms), and peak, are not sufficient for characterizing the energy in sounds such as those generated by pile driving strikes or the discharge of seismic airguns. Popper and Hastings (2009) proposed the use of the SEL, the time integral of the pressure squared for a single event, as a metric for setting pile-driving criteria (as well as for other impulsive sounds) (Table III). While the use of SEL is appropriate, the inclusion of other metrics is also necessary when setting criteria. The terms and expressions used in the field of underwater acoustics are defined in detail by the International Standards Organization (ISO).[6]

It is also important to understand that monitoring the sound levels actually received by animals can be difficult, as the sound sources themselves may be moving, and many animals themselves move in response to sounds and are therefore exposed to sound at different levels during their exposure.

H. Monitoring the temporal characteristics of sounds

It is commonplace to measure sounds as the levels averaged over periods of time, for example as the average level over 24 h, or over a shorter period. However, not all such monitoring takes account of variations in the timing of the sounds, or in their qualitative characteristics over that period (see Martin and Popper, 2016; Sertlek *et al.*, 2019).

TABLE III. Acoustic metrics. While these metrics refer to sound pressure, it should be noted that similar metrics can be applied to particle motion.

SPL_{peak}: The maximum overpressure or under- pressure exhibited by the sound pulse, measured either as the zero to peak level or the peak to peak level. This is easy to measure, and its biological relevance is high since several studies have noted a correlation between SPL and physical and behavioral impacts.

RMS sound level: The square root of the average of the squared pressures of the total waveform. RMS is most commonly used for longer-duration sounds such as those produced by continuous noise sources.

SEL: The SEL sums the acoustic energy over a measurement period (e.g., 1 sec), and effectively takes account of both the SPL of the sound source and the duration of the sound. It is a measure that can be summed across repeated emissions to give an overall measure of sound energy over a period of time.

SEL_{ss}: The SEL_{ss} is the value of a single pulse of sound.

SEL_{cum}: The cumulative value of several pulses over a given period of time. The SEL_{cum} can be estimated from a representative value and the number of strikes that would be required to place the pile at its final depth by using the equation:

$$SEL_{cum} = SEL_{ss} + 10 \log (\text{number of strikes})$$

This assumes that all strikes have the same SEL value and that a fish would continuously be exposed to pulses with the same SEL, which is never actually the case. This means that it is important to specify both the number of pulses, and any variations in the SEL_{ss} levels over time, when the SEL_{cum} is used.

Importantly, there is the issue of whether the sound is at the same level over the monitoring period, or whether the level varies, or the sound is intermittent, switching on and off. In some cases, there may be high sound levels over short time intervals within the overall duration of the measurement period. Moreover, the temporal structure of a continuous sound may be rather different to that of a pure tone or white noise (continuous sound containing many frequencies with equal intensities). Some continuous sounds may be potentially more damaging than other continuous sounds, especially where impulsive sounds with rapid rise times are embedded in steady-state noise.

Indeed, it is clear that exposure to such complex noise produces substantially greater hearing loss in mammals than exposure to Gaussian noise (a type of noise whose probability density function is same as that of the normal frequency distribution) (Goley *et al.*, 2011), and it is reasonable to assume that the same is likely to be the case for all vertebrates. The characteristics of complex noise may include a variety of features (NMFS, 2018), which are often described by terms, including "roughness," and "sharpness," although the definitions of such terms often do not really provide a full description of the complexities of many anthropogenic (and other) sounds. Metrics have been proposed to cover such differences and are listed below. All of these metrics are computed from time series of the data. However, there is not always consistency in how the metrics are used, and we have as of yet no real understanding of the implications of how sounds with various characteristics may impact fishes (or any marine animal, for that matter). These metrics are mentioned here not because they are in current use with regard to determining criteria for fishes, but because they need to be considered in the future when we have a better understanding of how anthropogenic sounds affect fishes. Indeed, support for considering such terms comes from studies on mammals where the effects of sound on the auditory systems of these animals have been studied more extensively.

One metric that is seeing wider use in mammalian studies, and which is beginning to be mentioned for both marine mammals and fishes, is kurtosis. Kurtosis is the most commonly used measure of the asymmetry of a probability distribution for the amplitude of a time-series (Henderson and Hamernik, 2012). Kurtosis is the fourth moment of the time series divided by the square of the second moment. NMFS (2018) defines kurtosis as a "statistical quantity that represents the impulsiveness ("peakedness") of the event (e.g., Hamernik *et al.*, 2003; Davis *et al.*, 2009). The kurtosis of Gaussian distributed random data is 3, while time-series with strong sinusoidal signals have a kurtosis in the range of 0–3 and time series with transients have kurtosis above 3. The value of kurtosis depends on a number of factors including the signal rise times and the pulse rate of impulsive sounds.

Other metrics that potentially should be considered with regard to fishes include:

- Skewness: a measure of the asymmetry in the probability distribution for the amplitude of a time-series.
- The Crest Factor: the peak SPL minus the rms SPL over some duration, computed for each minute of data.
- The Harris Impulse Factor: the maximum value for each minute of the impulse time weighted SPL minus the slow time-weighted SPL (Harris, 1998).

Kurtosis and Crest Factor and Harris Impulse Factor are well correlated with one another and respond similarly to changes in the data, while the Skewness is less correlated with the other metrics. Kurtosis is often considered to be the most sensitive metric considered for measuring the temporal characteristics of sounds (Henderson and Hamernik, 2012). Changes in the temporal characteristics can change the severity of effects upon animals, including fishes (Popper and Hawkins, 2019).

The importance of considering Kurtosis in the future is that it has been shown to correlate with hearing loss in mammals. Most notably, Hamernik *et al.* (2003, 2007) and Davis *et al.* (2009) demonstrated that permanent threshold shift increased with Kurtosis, up to about a kurtosis of 40; above this threshold increasing kurtosis did not have an auditory effect, but increasing the energy did. In addition, it has been found that the higher the level of Kurtosis, the greater the damage to the auditory hair cells of the ear in terrestrial mammals (Zhao *et al.*, 2010). The extent of auditory effects is related to the bandwidth of the transients that make a sound non-Gaussian, with wider bandwidths resulting in stronger effects (Zhao *et al.*, 2010). At least in mammals, Kurtosis is a good predictor for auditory effects whether the source of non-Gaussian variability are impulses or not. The temporal characteristics of underwater sounds should be considered in any future investigations of the effects of sounds on marine life, perhaps using Kurtosis. It may also be possible in the future to use machine learning algorithms on computers to derive information on the temporal characteristics of sounds, without relying on a single metric like Kurtosis.

VI. STUDYING THE EFFECTS OF SOUNDS UPON FISHES

One of the major issues in trying to assess the potential effects of sounds on fishes is that many fishes can be difficult to observe in their natural environment. Some behavioral observations on fishes can be done in the lab, but one has to question whether captive animals and particularly fishes that are confined to a small tank behave "normally" when exposed to a stimulus. Studies on some captive animals, even in large enclosures (e.g., zoos), support the notion that captive animals may not respond in the same way that they do to the same stimulus in the wild (e.g., Wright *et al.*, 2007; Gidna *et al.*, 2013). Experiments conducted in the laboratory, or within enclosures, can be used to address particular questions that cannot be answered with wild fish, provided the limitations are understood. Such experiments should be carefully adapted to the species so that they can show as much of their natural behavioral repertoire as possible.

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It is also the case that the acoustic stimuli utilized in confined aquaria and tanks in the laboratory may not reflect the actual properties of sound under open water conditions. As a result, experiments confined to aquaria and tanks in laboratories may not produce results that reflect outcomes that can be expected to occur under natural conditions (Calder *et al.*, 1982; Matt and Cook, 2009). Even if a sound seems similar to a human listener in a tank, or when recorded in the wild, the actual acoustic parameters in a tank may be very different, including the ratio of sound pressure to particle motion, and the direction of the particle motion. As a consequence, the fishes' response may differ in the two environments due to these differences in the acoustic environment. Some experiments can be done on fishes in the wild, using sonar systems (e.g., Hawkins *et al.*, 2014), underwater television (e.g., Roberts *et al.*, 2016), and perhaps acoustically tagged fish.

A. Biologically significant physical effects

Sound exposure criteria should identify when sound levels can be expected to cause physical changes whose direction, magnitude, and duration are biologically significant. This significance might rely on an index that quantifies physical or physiological injuries in fishes. An example would include the Fish Index of Trauma (FIT) model that was utilized in recent studies of effects of pile driving sounds on fishes (Halvorsen *et al.*, 2012). That model applies a mathematical weighting to each injury, depending upon its perceived severity.

While not endorsing the FIT model *per se*, it is important that, over time, a physical effects model be developed that can be widely accepted and easily used so that investigators and regulators will have a common understanding of when an effect occurs. At the same time, it must be recognized that the definition of a biologically significant physical effect is likely to be species specific and may depend on the size and condition of the fish. It is therefore necessary to specify a quantitative index for injury or physical damage for a particular species and size of fish.

Then, experiments must be carried out to monitor the value of the index occurring at different sound levels for a number of such fishes. One way of determining the index level is to prepare and examine the exposure-response relationship. Such relationships involve plotting the level of sound against either the degree of effect upon an individual or the proportion of exposed animals that respond in a specified way to the sound. In the first case, the index sound level can be specified in terms of a selected value. In the second case, the index sound level can be specified in terms of the proportion of fish, considered to be statistically significant, that reach that index level. Note that 50% is a widely accepted threshold for an event, such as for determination of the level of response by an individual animal, or a group of animals, to a sound or other stimulus.

B. Biologically significant behavioral responses

With behavioral responses, it is necessary to specify those responses that are likely to be important in terms of having measurable adverse effects upon one or more components of the animal's fitness by affecting its growth, development, longevity or reproductive success. The link between a behavioral response and these variables may be direct (for example, sound that causes a fish to avoid a spawning site) or it may be indirect (for example, alteration of a fish's energetics by reducing its feeding rate); however, the response should be linked to a biologically significant consequence (Gill *et al.*, 2001). And, at the same time, behavioral responses should not be defined in terms of minor behavioral changes, such as startle responses or transient movements from a site. Such responses may be highly relevant to survival during predator avoidance. However, they rarely have other implications for components of animal fitness. We suggest that most animals, including humans, will often show minor behavioral responses to anthropogenic stimuli without those responses having substantive effects on health, longevity, development, or reproductive success.

Behavioral responses may be defined in terms of the degree of change in extent, or the magnitude of movements, or changes in normal behavior patterns. Response indices can be defined, and a plot prepared of the mean response index for different sound levels. For behavioral responses, however, the detailed context of an animal's behavior, the environment and immediate ecological imperatives may well play an important role (Ellison *et al.*, 2012; Bruintjes and Radford, 2013; Shannon *et al.*, 2016). It is perhaps naive, and may even be inappropriate, to seek single values of particular metrics to define a particular level of response by an animal. Nevertheless, current risk analysis procedures typically focus on single values.

C. Deciding whether effects are detrimental to animals

The magnitude of an acoustic effect, whether it is physical or behavioral, often increases as the signal level increases. The initial levels may not be at all harmful. This raises the issue of whether the definition of a biologically significant effect involves deciding whether particular effects are seen as detrimental to the animal, either in terms of adverse effects upon individuals, upon populations, or even upon ecosystems. As discussed earlier, the two primary demographic components of fitness as points of reference for deciding when individual-level effects are detrimental to animals: (1) when it reduces an animal's probability of surviving to adulthood, or (2) when it reduces the animal's expected mean or median lifetime reproductive output. Changes in one or both of these components of fitness determine whether an effect is likely to be biologically significant and detrimental for individual organisms. However, any assessment of the effects of anthropogenic sounds should also consider the population-level consequences of these individual-level effects.

D. The need for control trials

Whether physical injury or behavioral responses are being considered, it is absolutely important to conduct control trials and to compare the responses during the control trials with those occurring during the test trials. The control trials, to be useful, must be identical with the test trials except for a single variable—in this case, the sound stimulus that is being investigated. The responses from the control trials can then be compared with the results from the sound exposure trials, to determine whether it is the sound exposure that has resulted in those responses, or whether other stimuli may be playing a part. It can sometimes be difficult to carry out control trials under field conditions, as the experimental and control trials may have to be carried out at different locations, or at different times. In those cases, great care has to be taken in the interpretation of the data to account for multiple variables. At the same time, it may be possible to account for these differences by having multiple sets of controls in order to eliminate different variables (e.g., Popper *et al.*, 2007).

VII. CURRENT SOUND EXPOSURE CRITERIA FOR FISHES

Some interim guidelines on criteria for sound exposure, suggesting sound levels that should not be exceeded, have been established for cetaceans and pinnipeds (e.g., Southall *et al.*, 2007; Southall *et al.*, 2019). Interim sound exposure criteria for the onset of physiological effects on fishes, for use on the United States west coast, were first proposed by the Fisheries Hydroacoustics Working Group (2008) (FHWG). The criteria were termed "interim" because it was understood by all parties that the criteria were based on limited information and would need to be updated as new research emerged.

More recently, a new set of interim criteria and associated guidelines were proposed (Popper *et al.*, 2014). These were based on much wider and more recent experiments, and these have raised the effective onset of effects levels, at least for physical effects, substantially. The criteria provided in this report were in the form of a set of tables to reflect that criteria may differ for different sound sources.

These interim criteria are being used rather widely now in the US and Europe, at least in an informal way as agencies move away from older criteria (especially those provided by the FHWG and the dB_{ht} concept of Nedwell *et al.*, 2007). Indeed, a recent comprehensive review of the literature (Popper *et al.*, 2019a) concluded that there is nothing in the literature since 2014 that would markedly change the 2014 criteria. At the same time, it continues to be clear that it is necessary to carry out work to fill the numerous data gaps (e.g., Hawkins *et al.*, 2015), and only then will it be possible to refine, update, and strengthen, the criteria.

Of particular importance, there are substantial concerns expressed about the scientific basis for the current behavioral criteria (Slabbekoorn *et al.*, 2010; Hawkins *et al.*, 2015; Andersson *et al.*, 2017; Faulkner *et al.*, 2018). There is a need to take into account differences in fish behavioral responses by carrying out research on different species in different behavioral contexts. A given species may react differently at different times of the day, as demonstrated for the sprat, *Sprattus sprattus*, by Hawkins *et al.* (2014), where the dense shoals break up at night. They may also react differently in different environments, as well as in different seasons of the year, and it is important to take these variations into account in setting new criteria.

Finally, there are concerns regarding current sound propagation models since they often do not consider actual sound propagation characteristics in shallow water. It is important to take account of the changes in particle motion levels, and to consider transmission along the substrate, taking account of differences in the type of substrate (Kugler *et al.*, 2007; Hastings, 2008).

Additional suggestions for interim guidelines come from reviews in Europe, and while these reports continue to suggest the need for new data to fill the aforementioned data gaps, they tend to adopt the 2014 Guidelines (Popper *et al.*, 2014) as the basis for work, until more data are available. A recent report (Andersson *et al.*, 2017) proposes to define the noise levels that can cause injury and other negative effects and, on this basis, recommends noise levels that can be used to establish guidance values for regulating underwater noise for Swedish waters and species such as the Atlantic cod, Atlantic herring, and for fish larvae and eggs. The units used include the SPL_{peak}, which it considers has a high relevance for behavioral effects, and the SEL, which it considers is the metric most related to hearing impairing effects. It uses both the SEL_{ss} and the SEL_{cum}.

The framework does not propose sound levels for flight behavior or TTS in fishes. It states that this is because, unlike physiological damage to internal organs, both flight behavior and hearing damage are linked to the species' specific sensitivity to frequency and sound intensity, following the idea that behavioral thresholds have to be determined in the context of species and behavioral situations.

It is evident that in order to develop future criteria, considerably more data will be needed on a variety of effects, as outlined in Table I. The issue, in each case, is the complexity of obtaining appropriate data, then applying it to improve acoustic criteria. It is evident that the Fisheries Hydroacoustic Working Group (2008) interim criteria are excessively conservative and do not reflect current knowledge. The 2014 Guidelines (Popper *et al.*, 2014) present updated interim criteria for pile driving (and other anthropogenic sources) that best reflect the post 2008 studies. Therefore, until additional data gaps are filled, it is recommended that the 2014 guidelines and criteria be adopted as reflecting the best available science (see also Faulkner *et al.*, 2018; Popper *et al.*, 2019a).

VIII. INFORMATION GAPS THAT MUST BE FILLED FOR THE DEVELOPMENT OF FUTURE GUIDELINES AND CRITERIA

Several recent papers provide a broad overview of the most critical issues that apply to all fishes (see Normandeau, 2012; Hawkins *et al.*, 2015; Popper and Hawkins, 2019; Popper *et al.*, 2019a). While they cover a broad range of areas for future research, there are several major themes that are particularly critical for most rapid filling in the data needed to update the current interim criteria. The most immediate and important areas of future research include:

- ***The selection of species***: It is critical that the species studied represent the broad range of species potentially affected by anthropogenic sounds but divided into groups based on their hearing capabilities (e.g., Table II). An important point is that it will be imperative to obtain data from multiple species, and a range of sizes/ages of fish within each species. This is because there is likely to be substantial variation in potential effects depending on differences in species anatomy, physiology, and behavioral responses to various stimuli.
- ***Behavioral responses to sounds***: There are numerous behavioral issues that need to be examined, including the sound levels that are likely to elicit behavioral responses, and responses to sound pressure versus responses to particle motion. Data are needed on general behavioral responses to sounds at different sound levels and how these responses change during the course of sound presentation, perhaps as the fish habituate to the sounds and/or temporarily show hearing losses due to the presence of persistent sounds. It is important to examine whether the responses of fishes differ when they are at different distances from the source. There is a particular need to examine variations in the levels of behavioral responses in parallel with detailed characterization of the sound fields, ideally using a variety of different sound measurement metrics to ascertain which aspects of the sounds are most important.
- ***Development of exposure/response data***: There are many different sound parameters such as signal level, cumulative effects, number of impulsive sounds, etc., and it is important to understand how such parameters potentially effect fishes. Such data will provide insight not only for understanding the onset of physical effects or behavioral effects but also for determining those levels at which potentially harmful effects start to occur. Such information will enable regulators and others to be able to make better decisions on sound exposure criteria, particularly if they are willing to accept the idea that some small effects may not have any impact on the fitness of the animal.
- ***Hearing***: There is a clear need for more data on the hearing sensitivity of fishes of interest and standardization of hearing measurements in order to correlate with sound levels (sound pressure and particle motion) for consideration of issues related to behavioral responses, masking, and TTS. Such studies need to determine hearing thresholds not only under quiet conditions, but also in the presence of masking signals, to determine the ability of the fish to discriminate signals of particular interest to them in the presence of anthropogenic and natural ambient noise. In some circumstances, masking may be more harmful than the behavioral responses to some anthropogenic sounds, as masking can reduce listening space, so that prey cannot detect predators, and predators cannot detect prey. In addition, more data are needed on the ability of fishes to discriminate between different sounds, based on acoustic features including their frequency, amplitude, direction, and temporal characteristics, etc. Such data are needed in order to determine if the presence of anthropogenic sound can alter how fishes are able to use natural sounds and distinguish sounds from different natural sources.
- ***Modeling of Sound Fields***: Once the effects of sounds on fishes have been defined, it is necessary to estimate the extent of those geographic areas over which those effects might take place. However, making such measurements is often difficult and time-consuming, and, in many cases, modeling of a sound field may be more efficient and effective in providing the information needed for regulatory purposes. Thus, it is necessary to continue to develop models that can be used to predict both sound pressure and particle motion levels at different distances from the source. Moreover, such models must take into consideration water of very different depths, ranging from midwater in the deep ocean (where simple models may be used) to very shallow waters of just off the ocean shore, and in lakes, rivers, and streams, as well as variance in sediments since this has a significant effect on sound propagation through the substrate, which may be especially important to benthic animals.
- ***Particle Motion***: While it is clear that the use of particle motion for establishing criteria is something that should be done in the future, the lack of data on how particle motion impacts fishes as well as the lack of easily used methods to measure particle motion currently precludes the use of particle motion There is a particular need to develop methodologies for the measurement and use of particle motion in Regulatory Activities, as well as a common terminology for expressing levels of particle motion, that are approved by the International Standards Organization (ISO) and/or the American National Standards Institute (ANSI).There is also a need to determine the potential effects of particle motion on fishes. Studies need to include behavioral responses, physical and physiological responses to particle motion, and detection of the directional components of the particle motion.
- ***Fitness Consequences***: There is also a need for conceptual models and data that explicitly links changes in fish hearing, physiology, behavior, spatial distribution, and ecological relationships (predator-prey) resulting from acoustic exposure to one or more component of fish fitness. As discussed earlier, the theoretical foundations necessary to link behavioral changes to changes in individual fitness and assessments based on energetics have been developed, but these concepts cannot yet be employed in risk assessments. Further development of these conceptual models and methods, particularly applied to the impacts of sound on fish, would promote the development of sound exposure criteria for fish.
- ***Population Impacts***: There is also a need to consider impacts upon fish populations, in addition to the effects

upon individuals. Such impacts are effects that, with some certainty, rise to the level of deleterious ecological significance for the viability or resilience of fish populations. Unlike the word "effect," which does not necessarily encompass significance, the word "impact" encompasses the severity, intensity, or duration of the effect upon animal populations and ecological communities. Such impacts can then be compared with those resulting from other stressors, including chemical pollution, fishing, pathogens, climate change, etc.

Moreover, there to be commonality in how research questions are approached. That is, there are many ways to do experiments, and each investigator will select a certain approach. However, there is no standardization in approach, and this has resulted, for example, in widely divergent hearing thresholds for the same species, as first pointed out by Chapman and Hawkins (1973) and later for goldfish by Fay (1988b) and Ladich and Fay (2013). Thus, without standardization of how experiments on all aspects of hearing are done, both from the perspective of acoustic setup and behavioral methodology, as well as in selection of animals, setting of criteria will not be possible.

Instead, what is needed is a legitimate approach to the physical nature of any hearing experiments (i.e., the acoustics) as well as to how one goes about measuring thresholds (Popper *et al.*, 2019b). For example, should all studies be done using behavioral methods, which essentially "ask" the fish what it can hear, and which require complete neural responses (as done for hearing thresholds in other animals). It is less certain that physiological measurements are acceptable, where the responses of the nervous system are monitored using electrical receivers, including the Auditory Evoked Potentials (AEPs) and the Auditory Brainstem Responses (ABRs). AEPs and ABRs monitor the signals generated by hair cells within the ears, nerve fibres, or groups of cells within the brain. They do not actually demonstrate that the fish is obtaining information that will change its behavior. Moreover, not only are standard approaches needed for determination of hearing thresholds for pure tones, but they are needed for measuring hearing of different duration sounds (thresholds for which are known to vary), as well as sounds of different spectra. Following from this, criteria would benefit from a better understanding of masking and critical bands, as well as intensity and frequency discrimination, all using methods based on standard procedures developed for humans and other animals. The one case where ABR may be acceptable is with regard to measures of hearing loss (TTS and PTS) in response to intense sounds.

Related to this is the need to have approaches that prevent the confliction of detection by the lateral line vs the ear. Finally, as it has been shown that there can be differences in hearing responses with animals with different developmental histories and possible genetics (Popper *et al.*, 2007; Wysocki *et al.*, 2007) as well as different temperatures (Wysocki *et al.*, 2009; Ladich and Schleinzer, 2015), these factors must also be accounted for when developing data to be used in criteria determination.

IX. CONCLUSIONS

The intention of this paper is to stimulate thinking among researchers, regulators, industry, and others about how one must approach developing criteria for effects of anthropogenic sound on fishes. Our focal argument is that, to date:

- There are few really useful data on the adverse effects of sounds on fishes to assist with setting criteria.
- We may not yet be asking the most important questions about the potential effects of sound on fishes.
- We have very poor understanding of the characteristics of the sounds that potentially affect fishes and how they propagate.
- There are numerous data gaps in our understanding of how different fishes detect and respond to sounds, to enable us to understand what sounds might or might not affect fishes adversely.
- The terminology used by regulators is often insufficiently defined, so that investigators, regulators, and others are often not "speaking the same language" in terms of the meaning of critical words.

[1]More information available at https://bit.ly/2v6OKrh.
[2]More information available at https://bit.ly/2BSf0MN.
[3]More information available at https://bit.ly/1Ee1v4R.
[4]More information available at https://bit.ly/31aUfDF.
[5]Note that we differentiate general term guidelines from the very specific Guidelines proposed by Popper *et al.* (2014) throughout this document. These are referred to in this document as the 2014 Guidelines.
[6]For more information, see https://www.iso.org/standard/62406.html.

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