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A validation of the dB_{ht} as a measure of the behavioural and auditory effects of underwater noise

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1 Introduction

This report proposes and offers validation of a frequency weighted scale, the dBht(*Species*), as a metric for the assessment of the behavioural and audiological effects on underwater animals of man-made underwater noise.

There is concern over the environmental effects that may result from man-made underwater noise caused by increasing exploitation and exploration of the coastal and deep sea. While the hazards associated with, for instance, the dispersal of toxic materials are now well understood, the understanding of the effects which may be associated with noise is in its infancy, despite its status as a significant underwater environmental issue. This results primarily from the lack of an objective scale (usually termed “metric”) which may be used to relate the observation of environmental effects to recorded levels of noise, and hence to allow both prediction of the effects of noise and the development of a body of case history relating noise, expressed in an appropriate metric, to effect to be developed.

It is common that much higher levels of noise are measured underwater than is the case in air, as a result of the relative incompressibility and density of water. These high levels often cause concern, and there have been many explanations offered as to why they should not have an undue effect on marine animals. For instance, it is often pointed out that the sound energy carried by noise in water is much lower than would be the case in air; however animals do not possess receptors that are sensitive to energy, so this explanation is fallacious. The authors suggest that the true explanation lies in the relative insensitivity of marine animals to sound.

Noise causes both auditory and non-auditory effects. The non-auditory effects of noise may be obvious, for instance when underwater blast results in floating dead fish. Other injuries, such as swim bladder rupture in fish, may be observed by observation and dissection of exposed individuals. These effects only occur at high levels of sound, for instance typically within tens of, or at most a few hundred metres from underwater blast, and hence affect relatively small areas and numbers of individuals (Nedwell and Edwards 2004).

The auditory effects of sound comprise temporary or permanent noise induced deafness, and the behavioural effects of underwater noise, typified by a species avoiding an area of high noise. Both of these are poorly understood, yet behavioural effects may have an influence over great ranges, often kilometres or tens of kilometres, reaching very much larger numbers of individuals. High noise levels have been cited as having the potential to impede communication amongst groups of animals, to drive them away from feeding or breeding grounds, to cause strandings, or to deflect them from migration routes.

The authors suggest that behavioural effects are primarily caused by noise that is uncomfortable or painfully loud to an animal. In order to quantify the “loudness” of a sound to a marine animal, the sensitivity of that animal to the noise must be assessed. Therefore, the frequencies contained in a sound must be considered when judging its likely effect.

Consider the significance of noise which is ultrasonic or infrasonic to a species, i.e. respectively above and below the range of hearing for that species, and hence inaudible. For man, sound is ultrasonic above about 20 kHz, and infrasonic below about 10 Hz. Bats (the loudest terrestrial animal) and dog whistles have no effect on humans, who do not perceive the sound because it is outside the auditory range for a human. Sounds above 1 kHz, such as generated by many sonar systems, are ultrasonic for most fish, which mainly have a limited hearing range of up to a few hundred Hz. Many marine mammals cannot perceive sounds below 1 kHz or so, and hence much (although not all) of the energy of a seismic airgun may be infrasonic to them.

Current regulatory limits for underwater noise are often expressed as a simple unweighted peak pressure, RMS pressure or unweighted Sound Exposure Level. However, the preceding considerations indicate that in order to objectively investigate the auditory and behavioural effects of underwater noise any valid scale must judge the loudness of the noise by reference to the frequency range and sensitivity of the animal's hearing. These considerations indicate the importance of considering hearing ability when evaluating the effect of underwater noise on marine animals. A number of recent reviews have highlighted this current shortfall, and have indicated that as the auditory system is frequency dependent, noise levels should be weighted for the manner in which the sound will be perceived for the marine receptor, in a similar approach to the way that noise assessments are conducted for humans (see for example Madsen *et al,* 2006).

For a metric to be widely acceptable to industry, pressure groups, regulators and government, it must be simple to understand and use, and must also be pan-specific, i.e. able to deal with a wide range of marine animals with greatly different hearing abilities, and a wide range of source types. However, it does not matter if it is complex to implement; for instance, one does not have to know how a sound level meter works to use it to measure noise in air.

A validated metric has many benefits which include:

- objective, rather than emotional, debates on environmental issues connected with noise;
- real problems to be sorted out from "red herrings" and hence the best use made of available resources;
- the drafting of clear and simple legislative or regulatory guidance ("the sound shall not exceed 90 dB$_{ht}$ at the stated range for any of the critical species...");
- a framework within which models may be used to estimate any effect of noise prior to an offshore activity being undertaken, and measurements of noise made and interpreted;
- allowing technically competent but non acoustically expert personnel to understand and evaluate the effects of noise;
- the provision of simple instrumentation, such as a Species Sound Level Meter (SSLM), enabling non-expert personnel to make evaluations of noise and its effects.

A distinction should be drawn between loudness and perception. For the purposes of this report, perception is defined as an objective measurement of the amount a noise is above the threshold of hearing. An objective measurement can therefore be made of the perception of a noise, and the dB$_{ht}$ metric is a measure of perception. Loudness, by contrast, is a subjective assessment of the apparent level of a noise to an animal. It is likely, however, that in most cases loudness and perception will be closely related.

For instance, the dB(A) scale is a measure of the perception of noise by humans. It is well known, however, that certain types of noise that are "unpleasant", like tonal noise from ripsaws in woodyards, has the same effect as other noise 5 – 10 dB higher in level. That is, the apparent loudness, and hence the effects of the noise, is greater than the perception would imply. This difference is applied as a "correction factor" in human noise exposure, allowing the loudness, and hence the effects of the noise, to be judged by reference to the human dB(A) perception scale.

2 A description of the dB_{ht}(*Species*) perception unit

The dB_{ht}(*Species*) provides a measurement of sound that allows the comparison of the effects of noise on a wide range of species. The loudness of a sound to a given species may be assessed by passing the sound through a filter that mimics the hearing ability of that species. The behaviour that is required of the filter is defined in terms of the measured hearing threshold of the animal. The metric therefore resembles the dB(A) scale that is used for the behavioural effects of noise on humans, and may be regarded as a generalisation of the approach to other species. It is a dB scale where the simple fixed reference pressure (typically 1 µPa for underwater sound) is replaced by the threshold of hearing of an animal, so the level is in “dBs referenced to hearing threshold”, hence the “ht” suffix. It should be noted, however, that since the hearing threshold will vary with frequency, the weighting will also be frequency dependent and the dB_{ht} must be calculated as an integral over frequency. The dB_{ht}(*Species*) level therefore corresponds to the likely loudness of the sound perceived by that species. Since different species have different hearing abilities, a given sound will have a different level on this scale for each species. Therefore, the animal for which the level is calculated (for a given noise source) must be specified as well as the corresponding level. This is achieved by appending the specific name to the level. For instance, a sound having a level 90 dB above a cod’s threshold may be specified as 90 dB_{ht}(*Gadus morhua*).

The equivalent view of the metric in the frequency domain is illustrated in Figure 1. The figure illustrates an idealised spectrum, and three idealised audiograms of two fish and a marine mammal. The part of the noise that can be perceived by the animal is represented by the area enclosed by the noise spectrum and the audiograms. It should be noted that the units of the metric are not sound pressure, but rather “hearing thresholds”. As a consequence it does not matter what units the hearing ability, and the noise, are expressed in as long as they are the same.

A benefit of the metric is that it yields realistic values for the level of the noise. While the unweighted levels of man-made noise are often apparently very high, the perceived levels are much lower because the sound will contain frequency components that the species cannot detect, and also because most marine species have high thresholds of perception of (are relatively insensitive to) sound.

The metric has an additional benefit in that it allows the perception of the sound for a species to be related to human experience; few people have an understanding of what a sound level of 200 dB re 1 µPa may mean, but if it is expressed for a given animal as 90 dB_{ht} – “or about the level you would perceive above your threshold in a room with a hifi at maximum level” – the experience becomes more relevant to humans.

The dB_{ht}(*Species*) scale rests on ten underlying hypotheses concerning the role of hearing in the animal, and the evolution of a species’ hearing to maximise the survival of a species.

1. **The role of loudness**. It is suggested that the sensation of uncomfortable or unbearable loudness is merely an evolutionary reaction designed to prevent damage to hearing when the perception of sound reaches a level where damage to hearing could be caused.
2. **Loudness and its relation to instinctive effects**. It is suggested that the behavioural effects of noise are primarily caused by a species taking an appropriate instinctive reaction in order to protect its hearing, typically avoidance, the strength of which depends on the loudness of the sound. The reaction to noise is therefore no different to that which would be taken when any stimulus reaches an unacceptable level, for instance in avoiding heat or bright light.
3. **Instinctive reaction vs loudness**. If it is accepted that the probability of an effect is likely to be associated with the loudness of a noise, instinctive reactions to noise must have

evolved to occur towards the upper end of the species' loudness range, since if they lay towards the lower end of the range the species would be in a perpetual state of panic or avoidance. The level for a given effect such as avoidance is however likely to be lower in “nervous” species (for instance, the grazers) than in “bold” (predatory) species.

4. **Loudness related to effect**. It is proposed that, irrespective of the source type, the “loudness” of a sound will tend to be the primary indicator of its effect. This means that different sources can be compared for a given species; for instance, if a fish reacts to an airgun at a given point on its dynamic range, it will tend to react to blast in the same way at the same perceived level.
5. **Limits of dynamic range**. No sensory mechanism has an infinite dynamic range. The dynamic range of hearing is set by physical constraints, from displacements of molecular dimensions at the lower end to displacements that are large enough to cause damage to hearing processes at the upper end. For human hearing, the dynamic range of hearing is about 130 dB. Above this immediate and traumatic hearing injury can occur. There are evolutionary reasons why other species will also have evolved to use this physically available dynamic range, and hence it is likely that well evolved hearers will have similar dynamic ranges. It should, however, be noted that at the upper and lower frequency limits of hearing the dynamic range can be compressed. This is allowed for in the human dB(A) scale by basing the frequency weighting on the 40-phon loudness contour, rather than on the actual hearing threshold. In practice, however, this makes little difference to the levels estimated. Since no equivalent information exists for marine animals, the estimates herein have been based on the threshold alone. The assumption in calculating the dB$_{ht}$(*Species*), therefore, is that the dynamic range of hearing remains constant with frequency, amd across a range of subjects.
6. **Reaction related to level above hearing threshold**. Current regulatory limits for noise expressed as a simple unweighted level ignore the wide differences in sensitivity and bandwidth of hearing for different species. These occur because the lower end of the dynamic range of hearing of a species will generally have evolved to be similar to the level of background noise in which the species live. Species living in a noisy environment are likely to possess a low sensitivity to sound, associated, however, with a high level at which traumatic injury will occur, and those living in a quiet environment are likely to have a high sensitivity to sound, associated with a low level at which which traumatic injury will occur. Species that make use of the background noise as a means of exploring and exploiting their environment may, however, have thresholds rather below the prevailing noise level.
7. **Avoidance of noise as a protection of hearing**. The upper end of the dynamic range, at and above which immediate, traumatic and irreversible hearing damage occurs, is about 130 dB in humans. However, below this, but at the upper end of the dynamic range, from about 85 dB to 130 dB, hearing damage occurs as a result of long-term exposure to noise. The damage is cumulative, initially presenting as temporary deafness following exposure, but resulting in small, irreversible and incremental permanent losses where exposure occurs over a long period. Noise at 90 dB above threshold for the human is perceived as being “very loud”, and rapidly becomes “unbearably loud” as it increases over 100 dB above threshold. It is suggested that the sensation of “unbearable loudness” and the consequent avoidance of noise is an evolutionary development which serves to protect hearing, and hence increases the chances of an individual’s survival. As a corollary of hypotheses 4, 5 and 6 all species with well developed hearing are likely to avoid sound when the level exceeds 90 dB above their hearing threshold, i.e. 90 dB$_{ht}$.
8. **Generalised and specific levels**. Since the levels expressed in this way will be different for animals with different hearing, where a specific animal is under consideration, the animal must be specified. The level would thus be quoted as dB$_{ht}$(*Species*), where the term in the brackets is the species under consideration. For instance, 90 dB$_{ht}$(*Phocoena*

phocoena) would be interpreted as "a sound level 90 dB above the hearing of a harbour porpoise". However, generalised comments are also possible, such as "animals will tend to react to sound at levels above 90 dB_{ht}".

9. **Cognitive and instinctive reactions**. The previous considerations have been discussed in the context of instinctive reactions, such as a species swimming away from a loud sound. However, cognitive reactions can also occur, such as a species avoiding a sound because it sounds like a predator. Unlike instinctive reactions, a strong cognitive reaction may happen at any perceivable level of noise (i.e. from 0 dB_{ht} upwards) if the species believes it signifies a threat. In general, man-made noise is unlikely to cause cognitive reactions, since it is very unlikely that it will have the characteristics of a predator's noise. However, some fish are thought to react to high frequency sonar signals because they have the characteristics of predator species such as dolphin echolocation clicks. For these cases a reaction may well occur at significantly lower levels of noise.
10. **The significance of an effect**. The dB_{ht} metric offers no guidance as to whether an effect will have any biological significance. A common reaction will be to flee high levels of noise, which may well have an implication for the species if such a reaction denies it access to a feeding or breeding area. However, other species, such as some flat fish, may react to sound by seeking cover (i.e. they become become "fixed to the spot"). There may in this case be no observable consequence of the noise. While the dB_{ht} metric may offer guidance as to the likelihood of a reaction, its importance has to be assessed by reference to biological criteria.

It is not claimed that the dB_{ht}(*Species*) scale is perfect. It is, for instance, known that some types of sound have a slightly greater effect on humans than their level in dB(A) would imply, i.e. the perception of such noise is not identical to its loudness. It is, however, suggested that an interpretation of noise made using this scale is likely to be much better related to its effect than, for instance, interpretations based on simple peak pressure, RMS pressure or unweighted sound exposure levels, all of which embody an assumption that all species have equal hearing sensitivity over a frequency range of indefinite bandwidth.

2.1 A provisional standard for dB_{ht}(*Species*) analysis

The dB_{ht}(*Species*) is based on interpreting noise to yield the level an animal would perceive. The steps in the process of forming the dB_{ht}(*Species*) level for a species are:

1. define the hearing ability of the animal, by means of good quality audiograms (hearing threshold as a function of frequency);
2. measure accurately the noise over the frequency band and dynamic range of the animal;
3. implement a filter that mimics the behaviour of the animal's hearing, so that the amount of noise falling within its hearing range may be found and weighted, according to its sensitivity at each frequency;
4. pass the sound through the filter and measure the output.

In each of these stages the information must be of an adequate quality if the final estimate is to be valid.

2.2 Types of audiograms

It is intuitively obvious that the quality of the scale used to quantify the effects of noise on a marine animal will be determined, at least in part, by the quality of the information that is available concerning its hearing. An audiogram is the fundamental measure of hearing, which presents the threshold of hearing of the subject as a function of frequency.

Nedwell *et al* (2004) summarises the available information regarding the audiograms of marine animals. It was noted that, in general, the available audiograms were of variable quality, and none of them are completely satisfactory for calculation of dB_{ht}(*Species*) levels. The audiometric data available at present, however, is accurate enough to distinguish marine mammals responding predominantly at high frequency (such as the harbour porpoise and botlenose dolphin) from those with sensitive mid-frequency hearing (pinnipeds) and low frequency hearers, such as fish. To make best use the metric will be important to provide audiograms to a suitable quality. It is, however, anticipated that in the event of the metric being generally adopted industry requirements will drive the provision of these on a case by case basis.

2.2.1 Behavioural audiograms

The principle of measuring a behavioural audiogram is that sound at a single frequency and at a specified level is played to the subject, typically as a pulsed tone. A uniform and calibrated sound field is created by means of, in air, loudspeakers or headphones, or, in water, projectors (underwater loudspeakers). A means is required to find whether the subject can hear the tone. In the case of human audiograms this is provided by the subject pressing a button when the tone can be heard. The level of the sound is reduced, and the test repeated. Eventually, a level of sound is found where the subject can no longer detect the sound, which is recorded as the threshold of hearing at that frequency. The measurement is typically repeated over a range of frequencies.

Behavioural audiograms are difficult to perform on marine animals as generally they require a lengthy training of the animal to react to a sound in a way that can be detected. Often the animal will be trained to perform an action for a food reward when a sound is played. If the sound is played at a given frequency and level, and the level gradually reduced, the point at which the action ceases may be taken as the threshold of hearing.

2.2.2 Evoked auditory potential audiograms

An alternative approach is to measure directly the evoked auditory potential, or electrical impulse in the auditory nerves, that results from the sound. This method have largely been used with fish, but some marine mammals have also been tested in this way.

In this approach, subcutaneous electrodes may be inserted in the subject’s head to contact an auditory end organ and directly measure the evoked voltage. Less invasively, the electrodes may also be placed cutaneously (on the skin of the subject’s head) to externally monitor activity in the VIIIth nerve and brainstem auditory nuclei. This latter approach is termed the ‘auditory brainstem response’ (ABR) method.

In a typical ABR measurement two electrodes are used, one of which is referred to as the ‘recording' electrode and the other as the ‘reference' electrode. The voltage between the two electrodes, of the order of µvolts, is input to the measuring apparatus. When the subject hears a signal there is a typical response waveform, the amplitude of which is dependent on the level of the sound it heard. The signal level is steadily reduced until the typical response pattern can no longer be discerned in the waveform, and the sound level at which this occurs is taken as the subject’s threshold. Signal averaging has to be used to ensure that the response can be detected above the background noise.

Audiograms derived from physiological measurements of this type may differ from those derived behaviourally since the latter include a cognitive element.

2.3 Shortcomings of audiograms

There are five factors in respect of the quality of audiograms that may influence the quality of an audiogram. These comprise:

2.3.1 Calibration and uniformity of the field

It is necessary to know exactly the acoustic field to which the species is exposed. In general, the pressure and particle velocity in an experimental tank will be complex, therefore careful measurements are required to define the sound field in the exact position where the animal is exposed. Usually the level of sound, in the absence of the animal, is recorded in the experimental tank for a wide range of level settings of the equipment generating the sound. The animal is then inserted into the field and the threshold of hearing of the animal is found. The threshold is then related to the equivalent free-field level of sound, rather than the actual level of sound adjacent to it. This method of measurement is termed an insertion measurement, since the level is measured prior to the subject being inserted into the field.

2.3.2 Background noise

Background noise has the potential to mask the tones presented to an animal during an audiogram measurement, causing artificially elevated thresholds. Some methods of estimation of audiograms, such as the ABR method, use an averaging procedure and hence are insensitive to noise. Others, such as the behavioural methods, rely on the animal being able to detect the tone above the background noise. It is therefore essential that the background noise is measured in any facility, and compared with the threshold measured.

2.3.3 Number of individuals tested

Inevitably marine animals will have varying acuity of hearing between individuals. Part of this variation will result from natural variability in ability, and it is possible that certain individuals may have suffered hearing damage as a result of disease processes, age, or as a result of traumatic exposure to sound. Consequently, the number of individuals tested in any given audiogram measurement has to be sufficient to establish reasonable confidence in the quality of the measurement.

2.3.4 Influence of the method on results

Where audiograms are reported by several authors for a single species, it is common that they vary considerably from author to author. It is probable that some of the variation results from the different experimental methodologies used. A degree of confidence that the results are correct arises where audiograms have been reported for the same species by different authors, under different experimental conditions, and using individuals drawn from different stocks.

2.3.5 Frequency and dynamic range of measurements

The ability to define the hearing range of a marine animal over a wide range of frequency and dynamic range is of crucial importance in accurately determining the dB$_{ht}$(*Species*) level of the noise.

Within the hearing frequency band for a given species, the sensitivity to sound will vary; usually the audiogram when plotted on a logarithmic frequency axis is roughly an inverted bell-shaped curve, with maximum hearing sensitivity near the centre. It is therefore convenient to split the hearing range into three bands:

- The “**peak hearing band**”, extending from the maximum sensitivity to, say, a frequency at which the hearing threshold is 12 dB higher than the peak value;
- A “**high frequency skirt**”, which extends upwards from the peak hearing band to the frequency at which the sound becomes ultrasonic for the species, say at 70 dB above the maximum sensitivity;
- A “**low frequency skirt**”, which extends downwards from the peak hearing band to the frequency at which the sound becomes infrasonic to the species.

One drawback of many reported audiograms is that they are often based on measurements at only a few frequency points, or the peak hearing band alone. They may be sufficient where the intent is to identify general features of a species’ use of sound, but are inadequate for detailed analysis of the effects of noise. This deficiency probably arises in part because the insensitivity of species to sound at the extremes of hearing means that high levels of sound are required to cause an evoked response, and such levels are difficult to generate.

When assessing the behavioural response of species to sound the entire hearing range must be known as a species may be equally affected by, say, a low level noise generating frequencies in the peak hearing band, or by a high level source generating frequencies at the extremes of the upper or lower skirts. In man, the human hearing range has been defined for practical purposes over a dynamic range of at least 70 dB (from the threshold at the most sensitive frequencies to the extremes at which hearing can be regarded as ultrasonic or infrasonic).

It will be noted that many of the audiograms reported are defined over very much smaller dynamic ranges. In many cases the peak hearing band is reasonably well reported; however the high frequency and low frequency skirts are generally poorly defined.

In principle it might be possible to extend the skirts of the audiogram to provide an estimate of the hearing sensitivity over a wide range. However, this may have a great bearing on the quality of the estimate of the dB_{ht} level. Consider the situation indicated in Figure 2. A noise source generates noise that is predominately at low frequencies. The estimate of the dB_{ht}(*Species*) level is represented by the area enclosed by the audiogram and the noise spectrum. However, if there are no measurements below a given frequency, an assumption has to be made as to the behaviour of the animal's hearing. Illustrated on the figure are three possible extrapolations of a measured audiogram. Firstly, it may be assumed that the slope of the audiogram is the same as that for a range of other animals – this might lead to the extrapolation marked 1. Secondly, it may be assumed that the slope of the audiogram would be maintained, which might lead to the extrapolation marked 2. Finally, it might be assumed that there is no hearing below the lowest measured frequency, which will lead to the extrapolation marked 3.

Each of these assumptions may be argued to be reasonable, but which is best can only be resolved by knowledge of the actual hearing sensitivity at the frequencies at which the source dominates. The quality of an estimate of a dB_{ht} level must therefore be judged in the light of the quantity of sound energy that falls outside the frequency range in which the audiogram is reliably known. Under the circumstances illustrated, the estimates of the dB_{ht} level would depend completely on the extrapolation and hence on assumed hearing ability, rather than on any measured audiogram data.

2.4 Measurements of hearing ability

The dB_{ht}(*Species*) scale is based on knowledge of the hearing ability of a species, i.e. on its audiogram. Originally it had been intended to base the experimental work on public domain audiograms. A review of the audiograms that are available in the public domain has been undertaken as part of this program of work (Nedwell *et al* 2004). Only a very small proportion of the marine species that are of commercial or environmental interest have had their audiograms measured, and it was found that, of those audiograms that are available, many are of a poor standard. Hence, it was necessary to develop the means to measure audiograms of the species used in the reaction tests.

2.4.1 ABR measurements of hearing

Hearing thresholds from any organism possessing the appropriate receptor mechanism are illustrated in an audiogram (Myrberg 1981), which presents the lowest level of sound that a species can hear as a function of frequency. Auditory perception by fish varies between species (Popper and Fay 1993; Yan *et al* 2000), with most falling into the category of being either a hearing specialist or generalist. Specialists, such as the carps and catfishes, have a connection between the swim bladder and inner ear, making these fish sensitive to the sound pressure component of an acoustic signal, conventionally measured in units of dB (re 1 µPa). However, generalists lack this connection and rely on the motion of water particles in a sound field to stimulate the sensory hairs of the ear (Hawkins and MacLennan 1976; Yan *et al* 2000). The volume of a swim bladder expands and contracts in a pressure field; in specialists, this motion is transmitted mechanically to the inner ear via the Weberian ossicles (Von Frisch 1938; Yan *et al* 2000) and allows hearing specialist fish to detect a wider bandwidth of frequency with greater sensitivity compared to generalist fish.

The use of behavioural paradigms to obtain fish audiograms is a method favoured by a number of authors and includes shock avoidance conditioning (Popper 1972; Coombs and Popper 1979; Myrberg and Spires 1980; Coombs and Popper 1982; McCormick and Popper 1984), or classical conditioning of heart rate (Chapman and Sand 1974; Offutt 1974; Hawkins and Johnstone 1978; Hawkins and Myrberg 1983; Mann, Lu and Popper 1997). However, the repeated administration of an electric shock during conditioning can preclude the use of these methodologies on ethical grounds. Non-invasive behavioural methodologies require that fish are trained to react in a specified and measurable way, e.g. by seeking food when a tone at a given frequency is presented (Yan and Popper 1992; Yan 1995); however, in practice, this type of behavioural method is very time consuming and only effective with species that are easy to train. The measurement of microphonics from auditory end organs during acoustic stimulation (Enger and Anderson 1967; Fay and Popper 1975; Fine 1981) can generate results more rapidly than from behavioural paradigms, though preparation can often be complex and require invasive surgery to implant the electrodes directly into the nerve (Enger and Anderson 1967). In addition, the electrodes may be restricted to a specific end organ or region of macula, thus an evoked potential may not necessarily represent the whole auditory pathway (Kenyon *et al* 1998).

The Auditory Brainstem Response (ABR) technique of measuring hearing thresholds has been successfully applied to both mammalian and non-mammalian vertebrates (Corwin *et al* 1982), elasmobranchs (Casper *et al* 2003), and marine invertebrates (Lovell *et al* 2005a). The non-invasive ABR technique is a practicable substitute for thresholds obtained behaviourally, recording far-field synchronous neural activity in the VIIIth nerve and auditory nuclei elicited by acoustic stimuli (Jewett 1970; Jewett and Williston 1971; Jacobson 1985; Kenyon *et al* 1998). ABR measurements are used routinely in the clinical evaluation of human hearing (Jacobson 1985) and allow for the determination of thresholds from uncooperative or inattentive subjects and in situations where preferred behavioural methods cannot be readily applied. An ABR trace is formed by averaging conglomerate responses of peak potentials arising from centres in the auditory pathways extending from the periphery of the VIIIth nerve and reflects electrophysiological activity chiefly from the inner ear and auditory nerve to the midbrain (Corwin *et al* 1982; Overbeck and Church 1992).

Several ABR studies have focused on measuring the hearing abilities of the goldfish, *Carrasius auratus*, stimulated with tone bursts presented through a projector mounted in air above the holding tank (Kenyon *et al* 1998; Yan *et al* 2000). In addition, Fay and Popper (1975) recorded microphonic potentials from the saccule of the African mouthbreeders (*Tilapia macrocephala*) and the catfish (*Ictalurus nebulosus*), using an air-mounted projector fixed below a 250 mm diameter PVC cylinder with a floor made from “Rho C” rubber. A loudspeaker with a diameter of 200 mm was suspended facing upwards 250 mm below the test tank in an airtight extension of the cylinder. In the present study the hearing thresholds were acquired using submerged projectors and a setup similar to the one used by Lovell *et al* (2005a) when measuring the hearing abilities of the silver carp (*Hypopthalmichthys molitrix*) and bighead carp (*Aristichthysc nobilis*). In addition, one of the species selected for this study for comparative purposes, the salmon (*Salmo salar*), has a behavioural audiogram by Hawkins and Johnstone (1978).

2.4.2 Details of the ABR method

A significant difference between the ABR measurements made by the authors and many of those reported in the preceding literature is in the complete submergence of the test subject. Many audiograms rely on the head of the subject (at the position of the electrodes) emerging from the water. Completely submerging the subject makes the experiment more challenging because it is extremely difficult to waterproof the electrodes, which is essential to remove electrical interference, and to establish a good electrical signal path between the fish and the electrodes. However, the acoustic field at the water surface is completely unrepresentative of the typical fields a marine animal will encounter, since the acoustic pressure tends to zero and the particle velocity to a maximum. While easier to perform, the results of an experiment conducted at the water surface are very difficult to interpret. Hence, measurements were made in a 1 m cube steel tank with the subject at roughly the centre.

The ABR measurements of hearing thresholds were made using "Brainwave", a proprietary control and analysis programme developed by Subacoustech and written in the LabView 7 environment. A schematic of the equipment used to provide audiometric measurements can be found in Lovell *et al* (2005b). The sound field in the experimental water tank was generated by means of two Fish Guidance Systems Ltd. Mk II 15-100 Sound Projectors; with the stimulus sound amplified using a Subacoustech Brainwave power amplifier. These faced each other at a distance of 200 mm, with the inner ears of the fish arranged midway on the axis connecting the centres of the two projectors. The projectors could be driven in the same phase, such that a pressure maximum was generated at the centrepoint between the projectors, associated with a particle velocity null. The projectors could also be driven in opposite phases, so that a particle velocity maximum could be generated at the centrepoint, but in this case associated with a pressure null. These two modes of operation were used to separate the response of the fish to pressure and particle velocity respectively.

Audiograms were measured for goldfish (*Carrasius auratus*), bream (*Abramis brama*), flounder (*Platichthys flesus*) and sandsmelt (*Atheriner presbyter*). Audiograms for the pouting (*Trisopterus luscus*), rockling (*Ciliata mustela*) and smelt (*Osmerus eperlanus*) were attempted, but were unsuccessful within the limited budget and timescale available due to handling problems with the fish. As a result of other work, a further audiogram was also obtained for bighead carp using the same apparatus, which has been used herein.

The fish were kept in large 3 m x 3 m x 1 m tanks containing either freshwater or seawater as required. The water temperature in the holding tanks and test tank ranged between 18.2 and 18.6ºC over a 24 hour period; when not under experimental protocols the fish were provided with natural daylight.

The procedure used to acquire the Auditory Evoked Potentials (AEPs) was approved by the UK Home Office. The experiment is illustrated in Figures 3 and 4. The test subjects were placed in a flexible cradle formed from a soft nylon mesh rectangle saturated with fresh or seawater, then placed in a fine wire mesh cradle. Oxygenated water kept at a temperature of 18ºC was gravity fed at an adjustable flow rate of between 5 millilitres per second, for the small fish, to 10 millilitres per second for the large, and directed toward the gills through a soft rubber mouth tube. The fish were first placed lengthwise and centrally on a 160 mm x 120 mm rectangle of fine nylon netting, which was wrapped firmly around the body and tail, and the two sides of the net were held together using a clip. The clip was placed in a retort stand clamp fitted with ball joint electrode manipulator arms and the aerated water pipe. When positioning the electrodes the specimen and clamp were suspended over the test tank and aerated water was supplied to the fish, which was then lowered to a depth of 200 mm below the water surface for the duration of the test.

The electrophysiological response to acoustic stimulation was recorded using the two cutaneous electrodes positioned on the cranium of the fish adjacent to and spanning the VIIIth nerve, which were connected to the differential preamplifier by 1 m lengths of screened coaxial cable with an external diameter of 1.5 mm. The evoked response was amplified and digitised to 12 bits resolution and recorded. This process was repeated up to 300 times, though the evoked response was clearly visible after as few as 20 repetitions; the response was averaged to remove electrical interference caused by neural activities other than audition and the myogenic noise generated by muscular activity. Each measurement was repeated twice; this aids in separating the evoked response, which is the same from trace to trace, from the myogenic noise, which varies in two successive measurements.

The stimulus tones presented from the loudspeakers to the fish were calibrated using an insertion calibration. A Bruel and Kjaer Type 8106 Hydrophone (Serial Number 2256725) was placed in the tank and positioned exactly in the position the fish would have been. The hydrophone was calibrated and traceable to International Standards. The signal from the hydrophone was amplified using a Subacoustech PE6 preamplifier and digitised using a National Instruments DAQ-6062e interface card at a sample rate of 300 kS/s. In case of non-proportionality of the response of the loudspeaker, measurements of the sound pressure were taken for every amplitude and frequency setting that could be used. Consequently, a total of 110 individual calibration measurements were taken in each calibration process. These calibrated levels were then applied to the threshold defined by ABR measurement to provide calibrated audiograms with pressure levels traceable to International Standards.

Measurements of particle velocity were also made, using two calibrated Reson Type TC4104 hydrophones spaced 60 mm apart on the centre of the axis connecting the two projectors. These hydrophones were used in preference to the Bruel and Kjaer hydrophones because the phase error was found to be less, which is important for particle velocity measurements.

The difference in outputs of the two hydrophones was found using a precision differential amplifier, to yield an estimate of the pressure gradient. The resulting signal was digitised and acquired and subsequently processed to yield the particle velocity of the sound field using the pressure gradient technique of Fahy (1995).

2.4.3 Measurement results

2.4.3.1 The pouting (Trisopterus luscus)

Unfortunately, due to supply and handling problems, it was only possible to obtain an audiogram for one individual of the pouting (*Trisopterus luscus*), a hearing generalist.

Figure 5 illustrates typical sets of acoustic brainstem responses in response to tone bursts from 100 Hz to 300 Hz. Figure 6 illustrates responses for the frequency range of 400 Hz to 1000 Hz. These were acquired as the stimulus intensity was successively reduced in steps of between 2 dB to 0.5 B at threshold. In both figures, the EP waveforms are presented with a blue colour coding, whilst the red set of waveforms represent below threshold waveforms from each frequency tested.

The upper sets of curves in Figure 7 represent the sound pressure and particle velocity of the tone burst at threshold, with the projectors driven in particle velocity mode. The lowest thresholds recorded from *T. luscus* with the projectors driven in particle velocity mode were 160 dB (re. 1 µPa) (P) and 158 dB (re. 1 µPa) (PV), at 750 Hz. The upper curves clearly show that the “most” audible frequency to *T. luscus* in the experimental tank with the projectors driven in particle velocity mode is at 750 Hz. The lower sets of curves in Figure 7 represent the response of the fish with the projectors driven in pressure mode; the data points represented by open diamonds designate sound pressure and the closed designate the particle velocity. The lowest thresholds from *T. luscus* with the projectors in pressure mode were 97 dB (re. 1 µPa) (P) and 100 dB (re. 1 µPa) (PV), at frequencies of 200 Hz and 750 Hz.

2.4.3.2 The sand smelt (Atherina presbyter)

Audiograms were obtained from a total of 12 individuals of the hearing generalist, the sand smelt (*Atherina presbyter*). Figures 8 and 9 illustrate typical sets of acoustic brainstem responses in response to tone bursts from 100 Hz to 300 Hz and 400 Hz to 1000 Hz respectively. These were acquired as the stimulus intensity was successively reduced in steps of between 4 dB to 0.5 dB at threshold. In both figures, the EP waveforms are presented with a blue colour coding, whilst the red set of waveforms represent below threshold waveforms from each frequency tested.

The upper sets of curves in Figure 10 represent the sound pressure and particle velocity of the tone burst at threshold, with the projectors driven in particle velocity mode. The lowest thresholds recorded from *A. presbyter* with the projectors driven in particle velocity mode was 176 dB (re. 1 µPa) (P) and 169 dB (re. 1 µPa) (PV). The upper curves clearly show that the “most” audible frequency to *A. presbyter* in the experimental tank with the projectors driven in particle velocity mode is at 200 Hz. The lower sets of curves in Figure 10 represent the response of the fish with the projectors driven in pressure mode; the data points represents by open diamonds designate sound pressure and the closed designate the particle velocity. The lowest thresholds from *A. presbyter* with the projectors in pressure mode was 109 dB (re. 1 Pa) (P) and 98 dB (re. 1 µPa) (PV), again at 200 Hz.

2.4.3.3 The salmon (Salmo salar)

Audiograms were obtained from 2 individuals of the hearing generalist, the salmon (*Salmo salar*). Measurements were made of the audiogram of the salmon to allow their comparison with previously published audiograms. Figures 11 and 12 illustrate typical sets of acoustic brainstem responses to tone bursts from 100 Hz to 300 Hz, and from 400 Hz to 750 Hz respectively. These were acquired as the stimulus intensity was successively reduced in steps of between 4 dB to 0.5 dB at threshold. In both figures, the EP waveforms are presented with a blue colour coding, whilst the red set of waveforms represent below threshold waveforms from each frequency tested.

The upper sets of curves in Figure 13 represent the sound pressure and particle velocity of the tone burst at threshold, with the projectors driven in particle velocity mode; the open circles designate sound pressure and the closed designate the particle velocity. The lowest thresholds recorded from *S. salar* with the projectors driven in particle velocity mode was 177 dB (re. 1 µPa) (P) and 174 dB (re. 1 µPa) (PV) at 200 Hz. The lower sets of curves in Figure 13 represent the response of the fish with the projectors driven in pressure mode. The lowest thresholds from *S. salar* with the projectors in pressure mode was 112 dB (re. 1 µPa) (P) and 101 dB (re. 1 µPa) (PV), at a frequency of 200 Hz.

2.4.4 Discussion of results

The ABR generated hearing thresholds of sand smelt (*A. presbyter*), pouting (*T. luscus*) and salmon (*S. salar*). However, in the case of the results for *T. luscus* the results were deemed suspect as only one fish could be tested, and hence these results have not been used for the analysis herein.

The salmon audiogram generated with the projectors operated in pressure mode closely resembles the behavioural audiogram by Hawkins and Johnstone (1978), which is presented in Figure 14, along with the results from this study. According to Hawkins and Johnstone (1978), salmon respond only to low frequency tones (below 380 Hz), with particle motion rather than sound pressure providing the relevant stimulus. This is in agreement with the results of this study, though ABR thresholds at 100 Hz are around 15 dB higher than behavioural thresholds. This could be caused by ambient noise masking the EP; also, there is no clear link between ABR voltage and a behavioural response to sound. In normally hearing humans, Gorga *et al* (1988) found that ABR thresholds were higher than behavioural thresholds for all frequencies tested, especially from lower frequencies where intersubject variability was greatest.

2.4.5 Verification of ABR data

It is known that the frequency and intensity of a tone burst affects the latency of the evoked response (Corwin *et al* 1982; Kenyon *et al* 1998), as does the metabolic state of the organism (Corwin *et al* 1982). The latency of the evoked potentials from *T. luscus* can be observed in Figure 15, in response to the second sinusoid of a 200 Hz tone burst. The sound was attenuated in 4 dB steps, and the arrows show the vertex positive component issuing from the neural centres situated along the auditory pathway to the midbrain. The increase in the latency of the evoked potential in response to decreasing stimulus intensity is often used to verify that the averaged waveform is a product of auditory stimulation rather than a transient generated at the electrode tip (Kenyon *et al* 1998). Thus, the Inter-Peak Latency (IPL) cannot be accounted for acoustically, as transients and other artefacts directly associated with the stimulus sound would occur at the same time regardless of stimulus intensity.

3 Numerical implementation of the dB_{ht}

The calculation of the dB_{ht}, or sound level above a species' hearing threshold, requires the implementation of a frequency dependent weighting. When assessing the impact of airborne noise on humans using the dB(A) scale, weighting of sound pressure levels in octave bands is applied before integrating the sound power in each band to give an overall level. While octave bands offer a suitable resolution for tracking the frequency dependant sensitivity of human hearing, it has been found that an octave band filter network would not adequately represent the rapid changes in sensitivity that occur in many audiograms.

Another option is to approximate the animal's hearing ability with one digital filter having continuously variable behaviour in the frequency domain. The advantages include its applicability to all audiograms, whatever the response. Also, since it is a time domain operation, it directly yields weighted time histories, which may then be processed to yield peak levels, RMS levels or other quantities as required. In addition, the approach may be implemented equally well in software on a computer or as a hardware filter. The objectives of the filter design technique are to accurately represent the measured audiogram, and to provide a simple and repeatable method for calculating the sound level above an animal's hearing threshold. It must also be flexible enough to allow filter design from a wide variety of audiograms, and the implementation of the filter on a wide variety of systems. These points, and the objectives outlined above, have led to the conclusion that the windowed inverse Fourier transform method of designing FIR (finite impulse response) filters is best suited to this task.

A major advantage of the FIR approach is that it is relatively simple to incorporate the filter coefficients into efficient software filters operating in a high or low level language on a computer, or as simple hardware filters. These may be used to offer “species sound level meters” which are an analogue of the meters used to measure the effects of sound on humans. Such meters would enable simple measurements of noise to be made in biologically meaningful units by non acoustically expert users.

The windowed inverse Fourier transform method relies on the frequency response of a FIR filter being the Fourier transform of its impulse response. By composing an idealised response in the frequency domain, the coefficients of a FIR filter may be obtained. This method requires a repeatable technique for designing the filter's frequency response from any given audiogram.

Using this technique, the first step in creating the filter is the formation of pressure thresholds as a function of frequency based on an audiogram. Audiograms will in general be measured in a way that does not lend itself to filter design, and assumptions must be made to define the response at frequencies where no threshold measurements have been taken. As noted in the previous section, this applies in particular to both the high and low frequency skirts which may not have been measured.

In general three frequency bands must be considered. That of most interest contains the measured pressure thresholds. This will initially be specified for a set of frequencies that will usually not be of the desired spacing for the filter, and hence must be interpolated. Above and below this range will be regions where the animal's hearing ability is not specified. Here a response must be assumed. Possible assumptions include the last measured value, a level below the peak sensitivity and, where the audiogram is the characteristic 'U' shape, a decreasing sensitivity of a similar slope to the last few measured points on the audiogram. All of these assumptions minimise the contribution of frequencies outside the range of the measured audiogram. In filter design terms, they may be considered, at either side of the measured audiogram, as the higher and lower stop band response.

The pressure thresholds must be defined every Δf Hz, between 0 Hz and $f_s/2$, where f_s is the sampling frequency of the time history to be weighted. The pressure thresholds as a function of frequency or $|P_{ht}(f_k)|$, are summarised in Table 1.

$\lvert P_{ht}(f_k)\rvert_{k=0\ldots l-1}$	Lower stop band response; f_l is the lowest frequency of the measured thresholds.
$\lvert P_{ht}(f_k)\rvert_{k=l\ldots h}$	Measured pressure thresholds (interpolated): f_l and f_h are respectively the lowest and highest frequencies of the measured thresholds.
$\lvert P_{ht}(f_k)\rvert_{k=h+1\ldots N/2}$	Higher stop band response; N is the filter length.

Table 1. Pressure thresholds as a function of frequency.

3.1 Reference pressure

Audiograms give pressure thresholds, but what is required is the ratio of measured pressure to threshold pressure. For the calculation of dB(A) levels the octave band filter network applies weightings relative to a human's hearing threshold at 1 kHz, which is 20 µPa. This is the standard reference unit for in-air acoustics. In underwater acoustics the standard reference unit is 1 µPa, which bears no relation to the hearing ability of marine animals. The dB_{ht}(*Species*) metric is a frequency dependent non-dimensional ratio of measured pressure to the pressure hearing threshold of an animal, and hence the units in which the noise is measured, and those in which the audiogram is presented, do not matter as long as they are the same.

3.2 Frequency response

The required filter response is the inverse of the pressure thresholds scaled by the reference pressure (if used) in subsequent decibel calculations.

$$|W_{ht}(f_k)| = \frac{P_{ref}}{|P_{ht}(f_k)|_{k=0\ldots N-1}}$$

Here, P_{ref} is the reference pressure to be used on subsequent deciBel calculations. W_{ht} is the ideal frequency response.

3.3 Filter coefficients

To calculate FIR filter coefficients, the inverse Fourier transform must be applied to the preceding equation.

$$h_{ht}(n) = \frac{1}{N}\sum_{k=0}^{N-1} |W_{ht}(f_k)| e^{j\frac{2\pi nk}{N}}$$

Although the frequency response of the filter will be accurate for all f_k, between these frequencies there may be significant divergence from the mean value of adjacent thresholds. The degree of this will be determined in part by the filter's length, and can be improved by windowing the filter coefficients.

The dBht level may be calculated as follows:

$$dB_{ht} = 20\log_{10}\left(\frac{\langle P(n) * h_{ht}(n)\rangle}{P_{ref}}\right)$$

where P(n) is a measured pressure time history in Pascals, sampled at f_s samples per second. The symbols * and <> denote convolution and RMS averaging respectively. It should be noted that whatever reference pressure is used in the final decibel calculation, the final dB_{ht} value will remain unchanged as the P_{ref} in the various equations cancel. The actual reference is the frequency dependent variable P_{ht}.

3.4 An example filter

A filter for calculating the dB_{ht}(*Salmo salar*) level has been developed using this technique. A salmon audiogram is shown in Figure 16; Figure 17(a) shows the ideal frequency response

$P_{ht}(f_k)$. This was created using the salmon audiogram and an upper and lower stop band response of 120 dB less than the animal's minimum pressure threshold. The response is defined to 24 kHz, or $f_s/2$ for a pressure time history sampled at 48000 samples per second. A pressure threshold is defined every 20 Hz, with logarithmic interpolation performed between the measured audiogram thresholds. The pressure thresholds were mirrored in the frequency domain before the filter's frequency response was calculated. In all these calculations the nominal reference unit, P_{ref}, has been chosen as 1 Pa; however the dB$_{ht}$(*Species*) is a dimensionless unit and whatever reference unit is used, the same value will result.

Applying an inverse Fourier transform results in the filter's impulse response function, $h_{ht}(n)$, which is shown in Figure 17(b). An N point Hamming window has been applied to the filter. The actual frequency response of the filter, as opposed to the ideal, is shown in Figure 17(c). It can be seen that the response does not exactly match that of the specified frequency response. At low frequencies there is a divergence away from the required response and the stop band response has not been achieved. At high frequencies the filter is similar to the desired response, but only achieves the stop band response at 20 kHz. This deviation of the true filter response from the ideal response results in inaccuracies in sound pressure level measurements. This is illustrated in Figure 17(d), which shows the measured audiogram along with the result of passing threshold level tones through the filter. It can be seen that at low frequencies the filter will tend to give an overestimate of the level above the animal's hearing threshold, with a maximum error of 8.7 dB at 31 Hz. However, in general, there is a reasonable match to the measured response.

3.5 Summary

In summary, the calculation of the dB$_{ht}$(*Species*) level is reasonably easily achieved by applying an FIR filter to a measured pressure time history. The method is robust, repeatable and can adapt to any audiogram, and can be implemented both in hardware and in software on computers of modest power.

4 Options for validation of the dB_{ht}

The research program detailed in this document aims to validate the dB_{ht}(*Species*) as a means of objectively evaluating the effects of noise on a wide range of species.

There are three means by which the effect of noise on species may be determined. These comprise:

1. **Measurements of efficiency of acoustic fish deflection (AFD) systems**. Use has been made of previously published results on the deflection efficiency of two AFD systems. First, a large acoustic fish guidance system is installed at the cooling water intake of the Doel nuclear power station in Belgium. The system uses large underwater projectors to generate a high level of low-frequency sound which deters fish from entering the intake. The second measurements were made on a Fish Guidance Systems Ltd acoustic guidance system installed on the hatchery raceway at the Wolff Hatchery, Havana, Illinois, USA. The system used sound to deter fish from passing from one side of the raceway to the other.
2. **Laboratory scale measurements**. Measurements have been made of the degree of reaction of a range of fish species with greatly differing hearing abilities to a wide range of signal types over a wide band of frequencies (impulsive, continuous, complex), and over a wide range of levels. The results indicate the degree of reaction of a number of individuals of several species to the different sounds. The sounds have been analysed using the dB_{ht} metric.
3. **Re-interpretation of public-domain information**. There are a number of published papers addressing the behavioural effects of underwater noise. In most cases there are no actual measurements of noise, and in the remainder the noise levels are specified in units which cannot be re-interpreted as dB_{ht} levels. However, in many cases the conditions of exposure, and the nature of the source, are sufficiently well specified that the dB_{ht} noise level can be estimated to a reasonable degree of accuracy. In that case the literature may be used to investigate noise level and effect.

These three approaches may be considered to be complementary experiments, the first gauging reactions of a large number of species and individuals to only one type and level of signal, the second gauging the reactions of a small number of individuals of several species to a range of signal types and levels, and the last providing an indication of the reaction of a wide range of species to a wide range of man-made noise sources. The three approaches are considered respectively in Sections 5, 6 and 7.

5 Re-evaluation of existing data for AFD systems

5.1 Measurements of AFD efficiency at Doel

The Doel nuclear power plant in Belgium draws its cooling water from the Scheldt Estuary near Antwerp; Figure 18 is a photograph of the station. Reactors Three and Four obtain their cooling water from an intake structure some 200 metres offshore. The cooling water inlet system is a cylindrical caisson with five underwater intake “windows”; the intake structure is illustrated in Figure 19. It is an important nursery area for marine and freshwater fish species, and prior to the installation of the AFD system it resulted in the loss of about 50 million individual fish per year. The AFD system was installed by Fish Guidance Systems Ltd in 1997 and uses twenty large electromagnetic projectors (FGS Type 30-600 Mk 2 Sound Projectors) to generate a sinusoid swept rapidly from 20 Hz to 600 Hz.

Any fish in the water are removed by the screens and backwashed into a trash container, which enabled a simple measurement of the percentage of fish deterred from entering the inlet by the sound to be made, by counting fish with the system on and the system off. Maes *et al* (2004) report a comprehensive set of measurements of the efficiency of the system conducted over the period from April 1997 to October 2001. Fish discharged from the cooling water were counted by staff from the Laboratory of Aquatic Ecology at the Katholieke Universiteit Leuven, Belgium. In total, about 350,000 fish were sampled, comprising 24 families and 41 species.

The results for which statistically significant results at a P<0.05 confidence level were obtained are shown in Table 2.

Species	Common Name	Efficiency (%)
Clupea harengus	Herring	94.7
Sprattus sprattus	Sprat	87.9
Dicentrarchus labrax	Bass	75.6
Osmerus esperlanus	Smelt	53.5
Perca fluviatilis	Perch	51.2
Solea solea	Sole	46.6
Pomatoschistus sp.	Goby	46.1
Abramis bjoerkna	Bream	40.1
Platichthys flesus	Flounder	37.7

Table 2. The efficiency (percentage reduction in catch) in the cooling water of the Doel nuclear power plant

Since the system relies on avoidance behaviour by the fish to prevent them from entering the inlet, the efficiency of the system is a reliable indicator of whether sound at the levels generated by the system at the cooling water inlet causes avoidance behaviour (i.e. a behavioural effect) on the fish. While both the sound signal and its level are fixed, since the hearing ability of the various species differs greatly the level relative to the various species’ hearing (i.e. the dB_{ht}(*Species*) level) is different for different species. The measurements therefore allow the dB_{ht}(*Species*) hypothesis (reaction related to dB_{ht}(*Species*) level) to be tested.

The underwater sound pressure with the system both on and off was recorded at the eight positions on the centreline of the inlet windows and at half inlet window depth indicated in Figure 19. The measurements were made using a Plessey spherical hydrophone, Serial Number 01319. The hydrophone was connected to a Bruel and Kjaer Type 2635 charge amplifier, Serial Number 1006781. The charge amplifier included a band pass filter with lower and upper cut off frequencies of 2 Hz and 30 kHz respectively. Following the charge amplifier the signal was recorded on a Sony TCD-D7 DAT machine, Serial Number 17370, for subsequent analysis using proprietary software. The average background noise level was found to be 132.2 dB re 1 µPa. This was well below the signal from the projectors, which was found to be typically at a Sound Pressure Level of 170 dB re 1 µPa.

An acoustic model was also used which provided modelling of the field with an average error of a dB or so.

The efficiency of the system for the species for which statistically significant results are available, and for which audiograms of sufficient quality are available, are presented in Table 3. The average dB_{ht}(*Species*) levels of the sound taken at one metre in front of the inlets have been calculated.

5.2 Measurements of AFD efficiency conducted at the Wolff Hatchery

A similar set of data is available as a result of the testing of a Fish Guidance Systems AFD system at the hatchery raceway at the Wolff Hatchery, Havana, Illinois, USA. The experiments were conducted by the Illinois Natural History Survey (Pegg 2002). The purpose of the installation was to test the efficiency of the acoustic system in blocking the migration of the non-indigenous Bighead Carp (*Aristichthys nobilis*) along waterways.

The AFD system was installed on a concrete raceway of dimensions 25 m long by 2.5 m wide by 1.8 m deep. In addition to the AFD installation, a second raceway was prepared with a dummy system as a control. The acoustic system comprised four FGS Type 15-100 projectors equispaced along an air pipe. The signal used was the same as that used at the Doel installation. Within a given experiment, for each trial, 11 bighead carp were placed in each raceway. The fish were observed as they approached the AFD system and the number of observed successful and unsuccessful attempts to pass the barrier recorded. In total 3,219 pass attempts were recorded. The system was found to be 57% efficient in deterring the passage of fish.

Subsequently, measurements of the audiogram of the bighead carp were made using the ABR system detailed in Section 3. They were found to be a relatively sensitive fish, having peaks in hearing sensitivity at a relatively high frequency of approximately 1500 Hz, where there was a lowest threshold of hearing at a Sound Pressure Level of approximately 106 dB re 1 µPa. The audiogram was used to estimate the dB_{ht}(*Aristichthys nobilis*) level of the sound. This is also tabulated in Table 3.

Common Name	Species	Data Source	dB_{ht} Level	Efficiency
Herring	Clupea harengus	Doel	82	94.7
Bass	Dicentrarchus labrax	Doel	56	58.5
Perch	Perca fluviatilis	Doel	55	51.2
Goby	Pomatoschistus sp.	Doel	44	46.1
Flounder	Platichthys flesus	Doel	37	37.7
Bighead carp	Aristichthys nobilis	Illinois	55	57.0

Table 3. The sound in dB_{ht}(Species) units vs the percentage avoidance.

Figure 20 illustrates the tabulated results as a graph relating the percentage avoidance of the sound to its dB_{ht} level. It is interesting to note that this analysis appears to indicate a clear and nearly linear dependence of the avoidance on the level of the noise above the species' threshold, i.e. the dB_{ht}(*Species*) level. An extrapolation of the fit implies that at levels of 90 dB_{ht}(*Species*) and above virtually all of a species will avoid the sound. Similarly, at levels of 10 dB_{ht}(*Species*) and below, no reaction occurs.

It is suggested that an adequate fit enabling the percentage avoidance, ø, avoiding a noise of dB_{ht}(*Species*) level L to be simply estimated from these results is:

$$ø = 100 \qquad (L > 90)$$

$$ø = 1.3\,L - 13 \qquad (10 < L < 89)$$

$$ø = 0 \qquad (L < 10)$$

This result is thought to be useful in that:

1. It is based on the measured avoidance of a large number of individuals of each species, such that the measurement is relatively reliable.
2. In the case of the Doel data, it is measured in an open water situation which is typical of the conditions of exposure for many applications of the dB_{ht}(*Species*) metric.
3. It is a probabilistic model that would prospectively enable either the number of individuals in a densely populated area affected by a given noise, or the probability of a given individual in a sparsely populated area being affected, to be estimated.

However, as a drawback it should be noted that the results are for only one signal type.

A second, and important, consideration is that the effects of habituation are not included in this analysis. It should be noted that as the Schelde Estuary is tidal and hence the fish would typically only briefly encounter the sound field, for perhaps a few seconds or tens of seconds. There is therefore no indication in these results, or in any of the results presented in this report, as to whether there may be habituation of individuals to sound over longer periods. It is thought likely that at lower levels of sound habituation may occur, where an individual will at first react, and then become accustomed to the noise and cease to react to it. However, at higher levels, where the stimulus to avoid the noise is greater, it is thought likely that sustained avoidance will occur.

5.3 Summary of open water results from Doel and the INHS

It may be summarised that the results of the open water measurements indicate:

1. The percentage of fish avoiding the noise from the AFD equipment at Doel and at the INHS show a clear dependence on the level of the noise above the species' threshold, i.e. the dB_{ht}(*Species*) level.
2. The analysis indicates a linear dependence of the avoidance on the dB_{ht}(*Species*) level, with a close fit of the data to the trend line.
3. An extrapolation of the fit implies that at levels of 90 dB_{ht}(*Species*) and above virtually all of a species will avoid the sound.
4. Similarly, at levels of 10 dB_{ht}(*Species*) and below, no reaction is predicted to occur.
5. It is noted, however, that the exposure is for a short time such that the effects of habituation are not addressed.

6 Reaction Testing

6.1 The method used for reaction testing

The dB$_{ht}$ hypothesis states that marine animals will respond to a sound when it is a given level above their threshold of hearing, measured in terms of the audiogram. The type of response may be determined by the level the sound is above the animal's threshold of hearing, i.e. its level in dB$_{ht}$(*Species*). The response of the fish may be in the form of a startle reaction, a change in the fish's activity level, or an avoidance response, and since these can be observed an experiment can be conducted to test the hypothesis.

The purpose of the experimental work reported on in this section was to test whether a given type of reaction would always occur at similar levels on the dB$_{ht}$(*Species*) scale, irrespective of species and signal type. Initially, it was decided to use the C-start (startle) reaction, which has previously been used for evaluation of the effect of airguns on fish. However, in the early stages of the experimental work it was found that it was difficult to elicit a startle response in most of the fish. After some consideration it became apparent that this was because startle responses only occur at levels that are towards the upper end of the dynamic range of hearing. For instance, in a human, startle occurs at levels in excess of 120 dB(A) (i.e. in the region of 120 dB$_{ht}$(*Homo sapiens*)); such levels arise, for instance, from firecrackers or from a dropped metal tea-tray. Milder avoidance reactions, however, occur at a lower level, and, for instance, humans will avoid, say, a road hammer, at a level of perhaps 90 dB(A) by crossing the road.

In the context of the environmental effect of underwater noise, it may be argued that avoidance is the most significant effect, since it may result in environmental effects (say, the impeding of salmon migration), economic effects (such as the loss of fishing) and emotive effects (such as the stranding of whales). It was therefore considered that avoidance, and not startle, was the appropriate quantity to address.

To establish the dB$_{ht}$ level at which an avoidance response is evoked the selected fish species were subjected to a set of seven electronically generated sounds. The tests were conducted in a large circular tank of 3 m diameter and 1 m water depth. The fish were placed in a mesh cage that was divided into two test sections using a visible dividing line to create a 'choice-chamber'. The size of the cage was sufficient to allow the fish to react, but also small enough to ensure that the sound field was of consistent level without a significant acoustic gradient. The sound field was generated via two FGS Model 300 Mark 2 sound projectors placed on either side of the cage, as seen in the photograph of Figure 21. The cage was monitored via an Aquacam™ monochrome underwater closed circuit television (CCTV) camera fitted above the cage. The test sound signals were generated by laptop computer using Windows™ Media Player, with the sound card connected to an FGS Model 400 power amplifier (rated at 450 W maximum RMS output). Each sound signal was calibrated to have a maximum level of 45 V RMS at the highest sound level tested, using an oscilloscope connected in parallel with the sound projector cables. A 12-way switchable attenuator was placed in line between the computer and the amplifier to attenuate the output level in 2 dB steps.

Table 4 indicates the species, sources of fish and size ranges of fish tested. The fish were kept in recirculating, aerated laboratory freshwater and sea water tanks for several days prior to testing.

Five fish of each species were tested over six replicate trial periods. Fish were initially carefully transferred to water from the test pool to avoid temperature shock. Once placed within the cage, an acclimation period of 20 minutes was allowed before each trial to allow fish to recover from any handling stress.

Throughout the trials the energised speaker was alternated from side-to-side in the cage to cancel out any possible side preference. Each sound was played at each of the twelve switchable levels for periods of 30 seconds. Observations of fish location were made via CCTV records before the sound was activated, 15 seconds into the trial and after 30 seconds, at which point the sound ceased. On each occasion the number of fish on the energised versus unenergised half of the cage was counted.

Common Name	Species	Source	Mean Length (mm)	Length Range (mm)
Flounder	Platichythys flesus	Sizewell and Barking power station	200	190 - 230
Goldfish	Carassius auratus	Rod and line from Calshot, Southampton Water	165	150 - 170
Rockling	Ciliata mustela	Shoream power station screens	180	170 - 185
Sand smelt	Atherina presbyter	Seine netting, Calshot, Southampton Water	80	65 - 85
Smelt	Osmerus eperlanus	Barking power station screens	120	110 - 140
Dab	Limanda limanda	Sizewell and Barking power station screens	180	160 - 200

Table 4. Details of fish used in reaction tests.

6.2 Results

The fish within the test cage were constantly observed to ascertain the point at which an avoidance response was generated. The seven test species showed differing levels of response.

Of the experimental species, reliable audiograms were found to be only available in the public domain for the goldfish. The pouting data has, however, been analysed by using the cod audiogram. While, as noted in the previous section, it was attempted to measure an audiogram for the species, it was found impossible to measure this to an adequate standard within the constraints of budget and timescale of the experiment. Therefore the audiogram of the cod was selected as the nearest gadoid species available, and because it has a similar morphology. It is thought that the relative levels of the various signals would be well modelled by this means, although the absolute level may vary between the two species. Audiograms were obtained for the flounder and sand smelt; consequently these results have been analysed and used herein.

There was no reaction in the case of flounder and dab. Initially, it was not certain why this was the case. Despite the level of sound reaching dB_{ht} levels at which a reaction would be expected, no avoidance reaction was noted. On careful inspection itt became evident, however, that this was due to the behaviour of this species when exposed to adverse stimuli. Flatfish rely on camouflage to avoid predators and hence their reaction to a challenge is to rest motionless on the bottom. Generally, they will only move when touched. It is therefore thought that this explains the lack of an observed avoidance reaction during the experiments. When exposed to noise a fish must determine whether it should flee, thereby exposing its presence to predators with consequent risk of predation, or stay motionless, thereby exposing itself to the risk of hearing damage. At the lower levels of noise to which the flounder was exposed during the laboratory tests, it is believed the result was an elective reaction in which the fish reacts by staying in position. It is possible that at higher levels of sound the instinct to flee would overcome the instinct to stay.

It is interesting to note that this differs from the results measured at Doel, where a positive reaction was noted for the flounder. Figure 22 illustrates the probable reason for this. Three reactions may occur when a fish approaches the cooling water intake on which the acoustic deterrent system is mounted:

1. the fish may enter the inlet,
2. the fish may approach the inlet, but avoid entering it as a result of an unacceptable level of noise, or

3. the fish may adopt a “hiding” response, diving to the seabed and staying in place.

It may be noted that the latter course of action would be measured as a positive response in the case of the Doel data, since the fish would be deterred from entering the inlet. However, in the case of the reaction tests, it would lead to a negative result, since a positive move away from the sound is required for it to register as an effect.

No reaction was noted for rockling. It is possible that the species is particularly insensitive to sound, as are many bottom-living species, but this cannot be demonstrated since it was not possible to obtain an audiogram of the species. For this reason the results have not been used in further analysis.

Reactions were noted for goldfish, pouting, sand smelt and smelt. However, at the levels of sound that could be generated in the experiment, the range of dB_{ht} values that could be spanned for smelt, which ranged from 0 dB_{ht} to only about 25 dB_{ht}, was insufficient to allow the results to be usefully analysed. In other words, the dynamic range of the experiment and the dynamic range of hearing of the fish did not overlap sufficiently. By comparison, the values for goldfish, which spanned from about 10 dB_{ht} up to nearly 80 dB_{ht}, and for pouting, which spanned from about 0 dB_{ht} up to nearly 70 dB_{ht}, enabled interpretation of the data and analysis of the trends as the level changed.

Figure 23 illustrates typical unprocessed fish reaction data. The figure illustrates the reaction of smelt (*Osmerus eperlandus*) to the sound signals. The sounds presented were recorded for each of the sound types, at every step in level at which they were presented. The experimenter was operating blind, i.e. had no information regarding the absolute sound levels. The reaction data recorded were subsequently calibrated so that the reaction could be calculated as a function of the dB_{ht}(*Species*) level. The percentage of the fish reacting is tabulated as a function of the level of the sound in steps. It may be seen that as the level of sound rises there is a corresponding increase in the number of fish reacting. The data were fitted with a linear regression indicating the best fit to the data; in addition the 95% confidence limits were plotted on each result; where the lower confidence limit falls below the zero line a significant avoidance level ($p>0.05$) is indicated.

The results are presented as peak dB_{ht} levels, for signals averaged over a tenth of a second. Since sounds that were significantly different in their temporal characteristics and frequency content were used in the experiment, this result implies that the reaction of the fish is well characterised by this peak dB_{ht} measure of the sound. This result is useful in implementing a Species Sound Level Meter as it implies that, provided the meter response can provide a 0.1 second peak level and the appropriate frequency weighting for a species, it may be used to compare significantly different sound types.

Figure 24 illustrates the calibrated avoidance results for the goldfish, for the case of the damped 50 Hz sinewave. The figure illustrates the mean of the percentage of fish avoiding the sound, versus the level of the sound in dB_{ht}(*Cassius auratus*) units. It is seen that there is a considerable degree of scatter in the results. Also illustrated on the figure is the best linear fit to the results. When calculating the best fit only the portion of the data where a reaction occurs (i.e. above 0 dB_{ht}) has been considered. Figure 25 presents the same results but for a swept sinewave, Figure 26 for modulated white noise, Figure 27 for unmodulated white noise, Figure 8 for a 100 Hz ping and Figure 29 for a 400 Hz ping.

The results, while scattered, indicate a clear dependence of the avoidance reaction on the level of the sound, with an increasing percentage of the fish reacting as the sound level increases. As an exception, the results for the 400 Hz ping, shown in Figure 29, do not apparently display this trend. It is thought that this is an artefact of the scatter of the results, rather than being a true representation of the behaviour of the fish to the sound. Otherwise, there is no indication that there is any significant difference in reaction to different sound types.

Figure 30 summarises the results for the goldfish. The figure presents the avoidance results for the goldfish, but in this case averaged over all sounds. In addition, the data falling within 10 dB_{ht} bins have been averaged. The plot presents the average of the data in each bin, and the 95% confidence limits for each average.

It may be seen that the data indicate a clear and increasing avoidance as the level of the noise increases. The threshold, below which no avoidance occurs, is at about 20 dB_{ht}. It is interesting to note that at the highest levels reached, of about 75 dB_{ht}(*Cassius auratus*), there was only a reaction by less than 30% of the subjects. This differs from the results of the open water measurements presented in the preceding section, where a reaction of about 85% of the subjects would be expected.

Figures 31 to 35 illustrate the calibrated avoidance results for the pouting. The data are less scattered than those for the goldfish. In all cases, for all sounds, the data indicate a similar, consistent and increasing response to the noise.

Figure 36 summarises the results for the pouting. The figure presents the avoidance results for the pouting, again averaged over all sounds and over 10 dB_{ht} bins. It may be seen that the results indicate a clear dependence of the avoidance reaction on the level of the sound, with an increasing percentage of the fish reacting as the sound level increases. The scatter in the results is less than was the case for the goldfish. The reaction to the sound is also greater than for the goldfish, with about 70% reacting at a level of 75 dB_{ht}(*Trisopterus luscus*). This is slightly lower than would be indicated by the open water results.

Figures 37 and 38 illustrate two typical results for the sand smelt. Unfortunately, because the sand smelt is a relatively insensitive species, the maximum level reached in the reaction experiments was only about 30 dB_{ht}(*Atherina presbyter*). As a result of the limited dynamic range, and the scatter of the results, it was not possible to use the data to identify any trend of increasing reaction with increasing level. This may be seen by the best fits to the data, which vary erratically from one plot to the other. Consequently, this data has not been used in any further analysis.

Figures 39 and 40 compare the best fits of the data for every sound for goldfish and pouting. It may be seen that there is a systematic difference between the results for the goldfish and those for the pouting. It is clear that the pouting displays a greater avoidance response to the noise than the goldfish. It is also interesting to note that the response of the pouting is more consistent than that for the goldfish. It may be seen that the difference does not lie in any calibration issue or error in the audiogram since the slope of the avoidance response (i.e. the rate of increase of avoidance with increasing level) is different for the two species. While calibration might alter the relative level of the two responses, it would not alter their slope.

There are various reasons why these differences between species might occur. First, it might be that the pouting is a relatively “nervous” species which reacts more strongly to the sound than is the case for the goldfish, perhaps, for example, because the pouting were taken from the wild, whilst goldfish have been bred for many generations in captivity and are more used to handling. However, from an evolutionary point of view, it might be expected that as the levels increase to a point where damage to hearing might occur, say of 90 to 100 dB_{ht}, the reaction by the goldfish would also tend to all fish reacting. Unfortunately, since it was not possible to reach such levels with the experimental equipment, this assertion cannot be tested.

Second, the differences might be due to the limited reaction opportunities in a simple experiment of this type. In a lake, for example, goldfish might swim for cover amongst macrophytic vegetation, but this option was not available to them in the experiments. While it would be possible to devise more complex experimental arenas, these would introduce further difficulties, for example by complicating the acoustic field and by tempting fish to remain in cover all the time. A way around this might be, for example, to devise a set-up where fish were provided with cover and the experiment measured the acoustic level required to flush them out. However, this approach further complicates the issue by introducing another cognitive lament, i.e. a choice between the perceived threat of the noise and the danger of leaving cover. Other experimental designs should nevertheless be considered.

6.3 Summary of reaction experiment results

It may be summarised that the results of the experimental reaction measurements indicate:

1. Some fish, such as flounder, are unsuitable as subjects for reaction experiments as their natural behavioural response is to hide by staying immoveable in one position. This consequently does not register as an avoidance response in the experiment.
2. For the two species for which there were valid results, goldfish and pouting, there was a systematic difference in response. The pouting displayed a greater avoidance response to the noise, and a greater increase of avoidance with increasing level than the goldfish.
3. In both cases, however the response was less than would be implied by the results of the open water experiments of Doel and the INHS with other species of fish.

6.4 Synthesis of the open water and laboratory reaction information

Figure 41 synthesises the open water reaction data gleaned from the Doel and INHS acoustic fish deflection systems with the laboratory reaction data. It should be noted that these are separate sets of data; however the requirements for a behavioural reaction to occur in a fish are similar for all the data sets.

While there is a wide scatter in the results, in all cases the data indicate an increase in reaction as the level increases. The goldfish appear to react less than the pouting, and the scatter is somewhat greater. Both sets of data for the tests in confined conditions indicate a lower response than for those in open water.

6.5 Discussion of the validity of confined experiments

There are several ways in which the experiments carried out in confined conditions differ from typical open water exposures. The results presented herein have indicated that there is a difference in how fish respond to noise in a laboratory tank *versus* open water conditions. Designing laboratory behavioural experiments, the findings of which can subsequently be applied to wild fish in open water, is inherently difficult. There are both acoustic and biological differences between the open water and constrained laboratory environments, as well as fish handling effects, which may cause differences in fish behaviour.

6.6 Statistics of laboratory experiments

While the scatter in the results presented in the previous section is large, there is nevertheless a clear indication that the reactions of fish in a ‘choice chamber’ experiment are different to those in open water conditions. A similar conclusion was drawn from data collected as part of a collaborative Masters research project between Subacoustech and the University of Newcastle-upon-Tyne to investigate the use of air-bubble curtains as a means to mitigate pile driving noise. The experimental animal selected for the work was also the common goldfish (*Carassius auratus*), which were exposed to playbacks of pile driving activities taken at the North Hoyle wind farm construction site. In the experiments there was a 6 – 10 dB acoustic gradient for the three sound exposure levels investigated, and the level was thought to be sufficient to cause a reaction by the goldfish. However, the experiments did not identify any of the four metrics used, of swim speed, distance travelled, path curvature or nearest neighbour distance (NND), as being a suitable and reliable indicator of a behavioural response. While statistically significant results were found for each of the four metrics investigated, the results were random and inconsistent with the conditions of exposure, including control experiments both with and without an air-bubble curtain.

Statistical results were equivocal and difficult to interpret and it was concluded that the experimental design needed further development before such data was publishable. However, observations of video recordings taken during fish sound exposure presentations showed an increasing frequency of startle and mild avoidance responses with increasing source levels. The maximum sound level presented was 86 dB_{ht}(*Carassius auratus*). These preliminary studies suggest that the usefulness of laboratory experiments would be increased with controlled experiments in open water conditions such as those carried out at Doel with native fish species.

6.7 Reactions in a choice chamber

Choice chamber investigations rely on the fish species under investigation distributing themselves evenly within the experimental arena and for the behavioural response of the fish to result in the majority of the experimental animals moving together in the same direction (in contrast to predator avoidance reactions such as ‘flash expansion’ and ‘split’ tactics (Pitcher and Parrish 1993)).

In many circumstances fish in open water conditions will exhibit a schooling response whereby, if a dominant individual of the shoal avoids a noise, the rest of the shoal will follow. This response may, however, be diminished or absent in confined conditions where that individual cannot move far. Where the species is territorial, the impetus to avoid the noise by moving away from its source will also be moderated by the pressure to stay away from other members of the shoal. There is also a risk that the behavioural responses of domesticated species such as the common goldfish may be different to that of wild species owing to learned behaviours.

6.8 Acoustic conditions

A suitable acoustic gradient from an area of relatively high-noise exposure to an area of low-noise exposure is required when looking for a ‘choice’ response by an experimental animal. This provides the fish with the incentive required for it to remain in the chamber of relatively low sound exposure for the time period under investigation. This may be absent in a shallow experimental pool, where the sound field may be confused by the presence of compliant boundaries such as the walls of the tank and the water surface, and by sound propagation through a hard floor or steel tank walls.

6.9 Comparison of open water and laboratory experiments

In general, it should be noted that the number of fish used in the laboratory reaction experiments reported herein were typically two or three orders of magnitude lower than the number counted in the open water experiments at Doel, and consequently the reliance that can be placed on the results is significantly lower as a result. In addition it is apparent that the behavior of fish in such confined conditions does not mirror their behavior in open water. Consequently, it must be concluded that, while it is relatively easy to conduct experiments under confined laboratory conditions, the results may be ambiguous and their interpretation unreliable or impossible.

It may also be noted that these reservations may also apply to trials in open water conditions, but where fish are exposed in confined conditions, such as in a cage.

The authors believe as a result of the studies presented herein that the best available methodology for evaluating behavioural effects such as avoidance lies in observations made under actual open water exposure, where the movement of individuals is uninhibited by the experimental conditions. Such observations might be made, for instance, during offshore piling or seismic surveys, using methods such as direct visual observation, counting methods, including netting or long lining, by indirect observation such as by the use of sidescan sonar, and by observation of individuals, such as by the use of acoustic tags and associated receivers.

In summary, it is thought on the basis of available information and on the basis of the experience gleaned during this investigation, that open water experiments are greatly to be preferred over laboratory experiments.

7 Re-interpretation of the open literature on observed effects of sound on marine animals

The effects of sound that may prospectively be addressed by the dB_{ht} metric include those which are addressed by the dB(A) metric for human noise exposure, which include behavioural effects such as avoidance reaction, the limit of tolerance, the onset of hearing damage presenting as a temporary threshold shift, and traumatic hearing loss.

Some information is available concerning such effects of noise on fish, marine mammals, and human divers, and this section re-interprets and uses that information.

7.1 Behavioural effects

7.1.1 Avoidance reaction

Some data is available (Terhune *et al* 2002) for the levels of sound which are required to deter species such as harbour seals (*Phoca vitulina*) from predation on fish stocks. Behavioural reactions have been observed at a distance of 2.9 km from a source having at an SPL of 195 dB re 1 µPa. Assuming spherical propagation, this equates to a level of about 55 dB_{ht}(*Phoca vitulina*).

Fjälling *et al* (1993) reports on the use of a Simrad acoustic harassment device (AHD) in reducing fish damage by grey seals (*Haliochoerus grypus*) during a 6-year fishery in the Bothnian Gulf of the Baltic Sea. The source level was 191 dB re 1 µPa @ 1 metre, or approximately 120 dB above the seal's threshold. The authors note that the sound level is high enough to cause discomfort and avoidance at a distance of the order 100 m. Assuming spherical propagation, this equates to a level of 80 dB_{ht}(*Haliochoerus grypus*).

Yurk and Trites (2000) reports on the use of an AHD system to deter harbour seals from predation on migrating salmonids. The work mainly used Airmar seal scarers which were mounted on bridge supports. The Source Level is quoted as 195 dB re 1 µPa @ 1 metre, at a frequency of 10 kHz. Observers stationed on the bridge were used to detect seals. Significantly fewer seals were noted when the deterrents were used than during control periods. If it is assumed that an observer might detect a seal at 200 metres, the level at this range may be calculated to be about 89 dB_{ht}(*Phoca vitulina*).

Possibly one of the best documented studies of the effects of offshore construction activity on marine mammals comes from the construction of the offshore wind farms at Horns Rev and Nysted. Data were collected as part of a monitoring program, covering a baseline period before construction of the wind farm, the construction period in 2002, and one year following construction of the wind farm in 2003. Data from acoustic dataloggers (T-PODs) and visual surveys conducted from ships confirmed the presence of harbour porpoises inside the wind farm area during all periods investigated. At both wind farms a substantial but short lived effect of pile driving was observed. At Nysted, an area with low porpoise density, there were strong negative reactions to the construction, where animals left the wind farm area almost completely, and the reference site 10 km away also appeared affected. In both cases there was a strong avoidance reaction, at distances of up to 15 km. Unfortunately this unique set of data is compromised by the fact that no accurate measurements of the actual noise level were made.

However, the conclusions agree well with recent measurements made by Subacoustech during similar operations. For instance, measurements were taken during an operation at the Barrow offshore wind farm site, which is located 7 km off Walney Island, Barrow, on the Cumbria coast. A series of calibrated underwater sound recordings were taken to measure the sound at various ranges during impact piling operations. The data were analysed in conventional and dB_{ht}(*Phocoena phocoena*) levels. It was found that the piling noise fell to a level of 90 dB_{ht}(*Phocoena phocoena*) at a distance of 11 km from the piling, within which range a strong avoidance reaction was therefore expected. At 15 km the level was about 85 dB_{ht}(*Phocoena phocoena*).

There is some information regarding the effects of the noise from seismic surveys, during which a high intensity sound pulse is emitted every few seconds by an array of air-guns. Broadband and high dynamic range recordings of the noise from seismic arrays were made by Nedwell *et al* (1999), and subsequently further analysed and reported in Nedwell *et al* (2003). The data were analysed in dB_{ht}(*Species*) units. The work presented the Source Level and Transmission Loss in these units, and also presented information for how the Sound Pressure Level depends on the size of the air-gun array. Information was tabulated that could be used to correct for differing airgun array sizes.

A detailed study of the effects of seismic noise on cod (*Gadus morhua*) was made by Engas *et al* (1993), which indicated greatly reduced catches of fish by long lines around areas where air-guns were being fired. The studies demonstrated reduced catches at 15 km away from the source, with catch reductions continuing five days after the firing was complete. The catch reductions probably resulted from the fish moving away from the seismic firing, although they could also have resulted from altered fish behaviour causing them to be less likely to take hooks. These results are supported by the results of the re-analysis of the data recorded by Subacoustech. The Source Level of this seismic array for cod, measured at 5 metres depth, was found to be 195 dB_{ht}(*Gadhus morhua*) @ 1 metre, associated with a Transmission Loss of 28 log(R) where R is the range in metres. At 15 km the level has been calculated to be 78 dB_{ht}(*Gadhus morhua*).

Goold (1996) monitored common dolphins (*Delphinus delphis*) before, during and after a seismic survey in the southern Irish Sea, and observed an avoidance reaction by the dolphins in the area monitored, which was 1 to 2 km from the survey vessel. The survey employed a 2120 cubic inch air-gun. Comparison of this observation with the reanalysis of similar seismic data acquired in the North Sea and reported in Nedwell *et al* (2003), and allowing for the different size of airgun, indicates that at a distance of 2 km the level would have been about 91 dB_{ht}(*Delphinus delphis*).

7.1.2 Threshold shifts

In humans temporary threshold shifts (TTS) caused by airborne noise occur at levels greater than 70 dB above human threshold in air.

Nachtigall *et al* (2004) reports on the measurements of temporary threshold shifts in the bottlenose dolphin, measured using an evoked response procedure. Sound within a 4 to 11 kHz bandwidth was presented for a period of 30 minutes at a level of 160 dB re 1 µPa to an animal in a pen at a depth of 1 metre. The signal was band pass filtered white noise. Threshold shifts were found, with a maximum at 5 minutes after exposure and occurring at the test frequencies. Using the audiogram of Johnson (1967), the level may be calculated to be about 97 dB_{ht}(*Tursiops truncatus*). The observation of a small and temporary threshold shift therefore agrees reasonably well with the effects that might be noted in human exposure at a similar dB_{ht} level.

Kastak *et al* (1999) reported TTS in three species of pinnipeds exposed to varying levels of octave band noise for periods of about 20 minutes. Centre frequencies from 100 to 2000 Hz were used. TTS was detected at levels in excess of 137 dB re 1 µPa for the harbour seal, 150 dB re 1 µPa for the sea lion, and 148 dB re 1 µPa for the elephant seal. Using the audiograms of Kastak and Schusterman (1998) these correspond to levels of approximately 71 dB_{ht}(*Phoca vitulina*), 78 dB_{ht}(*Zalophus sp.*) and 93 dB_{ht}(*Mirounga angustirostris*) respectively.

7.1.3 Physical hearing damage

Noise is well known as a cause of damage to the auditory structures in humans and terrestrial mammals. TTS is indeed an early indication of hearing loss. During each TTS a small degree of permanent hearing loss accumulates such that, after long exposure, a Permanent Threshold Shift (PTS) occurs (Richardson *et al*. 1995). PTS can also occur instantaneously from exposure to very high sound levels, such as during an explosion (Scheifele 1997). In humans, at levels exceeding 130 to 140 dB above threshold, a single exposure to an intense sound may result in a sudden permanent hearing loss caused by acoustic trauma, or mechanical injury to the sensory cells of the cochlea.

Cox *et al* (1986) exposed goldfish to pure tones at 250 Hz and 500 Hz at 204 and 197 dB re 1 µPa respectively for durations of approximately 2 hours. There was some indication of hair cell damage. Using the audiogram of Yan (2001), these equate to levels of approximately 130 and 133 dB_{ht}(*Cassius auratus*), although, if other audiograms are used, levels 10 dB_{ht} lower result.

Enger (1981) found that there was damage to the ciliary bundles in the inner ear of cod when exposed to sounds at several frequencies from 50 to 400 Hz at 180 dB re 1 µPa for 1 to 5 hours. These correspond to levels of up to105 dB_{ht}(*Gadus morhua*), based on the audiogram of Chapman and Hawkins (1973).

The results reviewed here for the sound exposure of fish and marine mammals agree well with effect that would be expected in humans exposd to similar dB_{ht} levels.

7.2 Divers

7.2.1 Underwater hearing threshold

Information on human divers is of value in the context of validation of the dB_{ht}, since human divers are able to hear underwater sound extremely well and, unlike fish or marine mammals, are able to report on its effects. In fact, the hearing thresholds data that is currently available (see Figure 42) indicates that over the frequency range from 400 Hz to 2 kHz human divers are the most sensitive receptor to underwater sound (Parvin *et al* 1995, Parvin 1998). This is because the human auditory system, like that of other terrestrial animals, has evolved to function in a low noise environment.

In the case of humans in air, the auditory system is able to perceive pressure changes at levels as low as 20 µPa (ie. approximately 26 dB re 1 µPa). In the underwater environment there is a considerable loss of hearing ability and the frequencies at which human divers are best able to perceive sound is also very different. Figure 42 indicates that peak underwater hearing for a bareheaded diver occurs at frequencies from 400 Hz to 1000 Hz, and is at a level of 67 dB re 1 µPa. (The error bars in the figure indicate one standard deviation error about the mean data at each frequency). The data therefore indicate that human divers may be more sensitive to the low frequency components of underwater sound than many species of marine mammal.

7.2.2 Aversion response

Studies in the UK by Parvin *et al* (2002) and in the US by Fothergill *et al* (2001) have shown that, when exposed to continuous wave sound at levels above 155 dB re 1 µPa RMS, in the frequency range from 500 Hz to 2500 Hz, there is a rapid increase in the aversion rating by SCUBA divers. The studies showed that the criterion for assessing an acceptable underwater sound exposure for recreational SCUBA divers is based not on injury or tolerance limit to the sound, but on the level of aversion to the sound, i.e. on a behavioural response. The tests in the US reported by Fothergill *et al* (2001) involved the psychophysical effects of underwater sound on twenty one volunteer recreational divers. The subjects were given a simple two choice reaction test to undertake during the dive whilst exposed to underwater sound signals at varying level.

Although none of the subjects aborted the dives in the controlled environment of the tests, an increasing number indicated that they would consider surfacing, aborting a dive, and complaining about the noise, when the incident sound levels increased above 155 dB re 1 µPa RMS. Based on the published hearing threshold for human divers (see Figure 42), this received level of sound varies from 63 dB_{ht} at the frequency at which divers are least sensitive to underwater sound in this frequency range (ie. 2500 Hz) to 88 dB_{ht} at the most sensitive test frequency (1000 Hz, where hearing threshold for divers is at 67 dB re 1 µPa RMS).

In comparison with other marine species, the analogy here is that recreational divers, by indicating that they would surface and abort an open water dive, are demonstrating an avoidance response to the sound.

7.2.3 Auditory injury

Smith *et al* (1996) conducted a comprehensive study of levels of underwater sound causing auditory injury to divers. The data in Table 5 are a summary of a number of prolonged exposures to underwater continuous wave sound. The data present the level of sound, for a 15 minute exposure, that caused a 10 dB TTS in divers. The data have been re-evaluated using the audiograms of Parvin *at al (*1995) to yield the corresponding dB_{ht} levels based on human submerged threshold. It may be noted that there is a significant variability of the results; this is characteristic of such measurements where different individuals may have greatly differing susceptibility to TTS.

The average of the results across frequency indicate that at levels of about 100 dB_{ht} and above a significant and measurable degree of temporary hearing loss occurs. It is interesting to note, however, that at the highest frequency, of 4 kHz, where the dynamic range of hearing is known to be less in human hearing, that the TTS occurs at a lower level.

	500 Hz (n=11)		1000 Hz (n=6)		2000 Hz (n=13)		4000 Hz (n=11)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
SPL in water	174.5	16.6	167.1	8.9	176.2	15.8	179.0	17.4
dB_{ht} level	100	16.6	100	8.9	97	15.8	93	17.4

Table 5. 15 minute exposure causing a 10 dB Temporary Threshold Shift in divers (Smith 1996) and corresponding dB_{ht} levels based on human submerged threshold.

It should be noted in the context of exposure of marine animals to sound that TTS is a symptom of a small but irreversible degree of permanent hearing loss, and hence that if this exposure were repeated on a regular daily basis then it would be expected to develop into a significant and permanent hearing loss.

7.2.4 Tolerance limit to underwater sound

Eight male divers without headgear were exposed to underwater pure tones of 4 seconds duration at frequencies of 880, 1000, 1400, 1760 and 2200 Hz, and swept signals from 900 to 1250 Hz, 1400 to 1800 Hz, and 1800 to 2200 Hz (Parvin *et al* 2002*)*. Due to the short durations of the exposures, no threshold shifts were observed in the pre/post dive audiometric data. Measurements of underwater human hearing threshold from Parvin *et al (*1995) may be used to calculate the equivalent dB_{ht} levels. The results are given in Table 6.

7.3 Summary

The re-interpretation of public domain literature on the response of marine mammals, fish and human divers to underwater sound supports the relationship where there is an increasing likelihood of a behavioural avoidance (aversion) response for received dB_{ht}(*Species*) levels from 55 to 90 dB_{ht}. Auditory injury occurs following prolonged exposure to levels of 90 dB_{ht} and above, with an increasing likelihood of auditory injury for exposures above 100 dB_{ht}. A few seconds of exposure at levels of approximately 130 dB_{ht}(Species) has been shown to cause auditory injury in marine mammals. The literature therefore demonstrates good agreement with the human airborne auditory injury model; the likelihood of injury is related to both the level of the incident sound above threshold and the duration of exposure, where the doubling of noise energy (3 dB increase) results in a halving of the acceptable exposure period (an equal energy relationship).

It should be noted that the subjects were well motivated divers who were aware that they were to be exposed to high levels of noise. Nevertheless, at levels of 100 dB$_{ht}$ and above, some divers were unable to tolerate the noise.

Test signal frequency (Hz)	Termination SPL (dB re 1 µPa)	Reason for termination	dB$_{ht}$ level
880	182	Sound affected balance, dizziness	112
1000	182	Sound affected balance, dizziness	115
1400	176	Uncomfortably loud, dizziness	100
1760	185	Loudness, dizziness	105
2200	185	Loudness	100
900 - 1250	179	Loudness	112
1400 - 1800	182	Loudness	116
1800 - 2200	185	Loudness	104
Average			108

Table 6. Tolerance limits and termination criteria for human exposure to underwater sound (Parvin et al 2002).

8 Cumulative injury from noise and the dB_{ht} $L_{ep,d}$

The concept of auditory injury from exposure to noise is well established for airborne sound exposure of humans. At a high enough level of sound traumatic hearing injury may occur even where the time of exposure is short. Injury of this type is normally associated with immediate and irreversible hearing loss. Injury also occurs at lower levels of noise where the period of exposure is long. In this case the degree of hearing damage depends on both the level of the noise and the duration of exposure to it. It has been established that for human exposure any sound over 90 decibels above human hearing threshold will eventually cause hearing damage. Exposure to noise at 90 dB for 8 hours a day will cause hearing damage; however, for every 3 dB increase in noise level, an equivalent amount of damage will occur in half the time. This is known as the "equal energy rule". For complex or time varying signals the degree of hearing damage has been related to the "noise dose" of the noise. The noise dose incorporates the equal energy rule and provides the continuous noise level containing the same sound energy as the time varying signal (the noise of equivalent power, or $L_{ep,\,d}$), and the duration of exposure.

The $L_{ep,\,d}$ used for human noise exposure is based on the A-weighting, and is hence based on the level above human threshold. The dB_{ht} therefore offers a means of translating the noise dose approach developed for human exposure to marine animals, and thus for assessing the cumulative effects of noise exposure on the hearing of marine animals. The annotation dB_{ht} $L_{ep,\,d}$ has been used to describe the equivalent dB_{ht}-weighted noise level.

For single exposure sounds Ward (1997) developed a level against exposure duration guide indicating that for sounds from 126 to 144 dB above hearing threshold (i.e. dB_{ht}), hearing injury can occur for exposure periods from 60 seconds to 1 second respectively. The data from Schlundt *et al* (2000) indicate that this effect translates to marine mammal exposure to underwater sound. In the study, short duration sound exposures (one second continuous wave) at levels of approximately 130 dB above hearing threshold caused a small TTS hearing injury in the bottlenose dolphin. The recent review by Madsen *et al* (2006) highlighted that experiments with marine mammals demonstrate a near linear relationship between sound exposure level and duration of exposure, i.e. they agree well with the equal energy rule.

Based on this principle, the same noise dose (and therefore potential for auditory injury) occurs, for instance, following an exposure of 90 dB above threshold for a period of 8 hours, 93 dB above threshold for a period of 4 hours, or 130 dB above threshold for a few seconds (see Table 7). Hearing impairment in the form of a TTS in hearing may occur where an animal is exposed to these levels and durations, and PTS will occur with repetitive exposure. The higher the noise dose above this limit the more rapid will be the damage. The trade off of time and level is only possible up to a level of 130 dB, since, as noted in Section 7, higher levels can cause traumatic injury, whereby sudden and irreversible hearing damage can occur.

Exposure Level dB(A) or dB_{ht}	Exposure Duration
90	8 hours
92	5 hours
99	1 hour
110	~ 5 minutes
120	~ 30 seconds
130	~ 3 seconds

Table 7. Comparison of noise exposure level and duration for the same cumulative 90 dB_{ht} $L_{ep,\,d}$ noise dose.

In summary, it is likely that hearing impairment will occur where fish or marine mammals are exposed to continuous or repeated high level underwater sound for relatively long periods of time. The noise dose that the animals will accumulate will depend on the incident level of the underwater sound, which varies with range, and hence with the behaviour of the animal, and the level and temporal characteristics of the noise source. While the animal may mitigate the effects of the noise by fleeing the vicinity of the source, this may be insufficient to prevent hearing damage if the level of the sound is high, or the swimming speed of the animal low.

At the current state of knowledge, the extension of the airborne noise dose methodology to marine species by the dB_{ht} metric is thought to offer the best methodology for assessing the cumulative effects of noise on hearing.

8.1 Static and fleeing animal models

To determine the likelihood of auditory injury from the cumulative effects of noise, one must first calculate the time varying dB_{ht} for the species, and then use that to calculate a continuous equivalent level $dB_{ht}\,L_{ep,\,d}$.

8.1.1 The static animal model

As a typical example of a high level sound source, consider a piling operation. A pile of 5 metres diameter may typically generate an unweighted peak-to-peak Source Level of 253 dB re 1 μPa @ 1 metre (see Parvin *et al* 2006). For the harbour porpoise, a marine mammal with sensitive hearing, the corresponding average perceived Source Level of the piling is about 164 dB_{ht}(*Phocoena phocoena*) @ 1 metre. For the herring, a fish with sensitive hearing, the corresponding average perceived Source Level of the piling is about 137 dB_{ht}(*Clupea harengus*) @ 1 metre.

For the harbour porpoise the area of greater than 130 dB_{ht} sound level, within which traumatic injury could occur, would extend to a range of about 50 m. Further away an acceptable noise dose of 90 $dB_{ht}\,L_{ep,\,d}$ would be received by an animal exposed for a period of 8 hours at a range of approximately 5 km. Outside this range the level is sufficiently low that auditory injury is unlikely to occur even following prolonged exposure to the sound.

For the herring the area of greater than 130 dB_{ht} sound level would only extend to a range of about 2 m. An acceptable noise dose would be received over a period of 8 hours at a range of approximately 220 m.

This form of noise dose modelling assumes a static animal, i.e. the animal makes no attempt to move away from the source of the noise. Where animals are constrained within a test environment, as is the case for the controlled marine mammal noise exposure tests that have been conducted (Schlundt *et al* 2000, for example), animals exposed to these noise dose levels have been shown to develop a temporary hearing impairment (TTS).

In summary, this example indicates that where an animal is exposed near to a source of noise the noise dose can rapidly exceed 90 $dB_{ht}\,L_{ep,\,d}$.

8.1.2 The fleeing animal model

Under open water conditions it is far more reasonable to assume that, at the high received sound levels associated with impact piling, animals will flee the construction area. The observational data from Tougaard *et al* (2003 and 2005) and Henriksen *et al* (2003) indicate that this is the case.

As the animal flees the source of the noise the noise level will fall and hence the noise dose will accumulate at a reducing rate. Intuitively, therefore, the greatest contribution to noise dose will be during the start of the exposure.

Figure 42 illustrates the cumulative noise dose for a herring in the vicinity of the preceding piling operation; however in this model the fish swims at 1 m/sec away from the piling operation. It may be seen that initially the noise dose accumulates rapidly, but that as the animal moves away from the source the noise dose rapidly approaches a final value. In the case of the fish starting at 5 m and 10 m the dose can exceed 90 $dB_{ht}\,L_{ep,\,d}$. This dose is just reached by an animal fleeing from a distance of 30 m from the piling. However, for ranges exceeding this, the fleeing response of the animal is sufficient to avoid an unacceptable noise dose being reached.

A similar result is seen in Figure 43, which illustrates the cumulative noise dose for a harbour porpoise. The critical hearing impairment range for the harbour porpoise in this case occurs at 150 m. An animal at this point at the start of piling operations, swimming at a rate of 1 m/sec, is just able to remove itself from the auditory injury zone before receiving a cumulative noise dose of 90 dB_{ht} $L_{ep, d}$.

In summary, fleeing high noise levels probably provides an effective mitigation to mobile animals such that cumulative injury is unlikely to occur. The static animal model is therefore generally biologically unrealistic.

8.2 Distribution modelling using the dB_{ht}

Further analysis conducted using the conclusions of the research presented in previous sections has indicated an interesting paradox. These may be conveniently illustrated using the results of the re-interpretation of the seismic data presented previously. The Source Level of the seismic array for cod, measured at 5 metres depth, was found to be 195 dB_{ht}(*Gadhus morhua*) @ 1 metre, associated with a Transmission Loss of 28 log(R),where R is the range in metres.

Figure 44 illustrates the proportion reacting as a function of the range. As might be expected the proportion of fish reacting falls as the range increases. However, it may be noted that as the range increases the area of sea affected increases. Paradoxically, the number of individuals therefore increases, implying that the effect of a noise source increases with range. This is illustrated in Figure 45, which shows the number of individuals affected per kilometre of range as a proportion of the total number affected; the population density is assumed to be constant. In essence, this paradox results because the number of individuals affected increases more rapidly with range than the effect of the noise reduces.

It is thought that the paradox probably results because the ability of an individual to habituate to the noise is ignored in the experimental work presented. It is likely that at high enough levels individuals would exhibit a sustained avoidance reaction, but for lower levels it is likely that an initial reaction would be followed by habituation and lack of further reaction.

As an exercise, a model was written where the avoidance reaction is:

- sustained for one hour, where the level is 90 dB_{ht} and above,
- immediately habituated to when the level is 60 dB_{ht} and lower, and
- decreases linearly with level between these limits.

In addition, it was assumed that:

- a cod can swim at 10 km/hr, and
- would swim away from the source, and
- the source is stationary.

The results are illustrated in Figure 44. The results illustrate the effects on the population in terms of the percentage change at a period of 1 hour after the commencement of the sound.

It may be seen that the model predicts that there will be no change in the population at ranges of 70 km or more. Near to the source, however, the sea is swept clear by the noise; at greater distances there is an increase in population caused by the displacement of the fish. It is interesting to note that these results appear to match the observations of Engas *et al* (1993) on distribution of cod during a seismic survey, which noted a decline near to the source but an increased population further away from the seismic operation.

These initial results indicate the importance of habituation in determining the overall effect of a noise source. It may also be noted that in the case of the Doel data contained herein it is unlikely that any fish encountered the sound for more than 10 seconds or so. It would be valuable to investigate the sustained avoidance of a noise source, say for 1, 10 and 30 minutes in addition to the 15 and 30 seconds response that has been measured and presented in this report. At present, this should be considered a shortfall of the present work in terms of the impact of low level exposure.

9 Criteria

On the basis of the information contained in this report, the following criteria are suggested for the effects of noise.

Level in dB_{ht}(*Species*)	**Effect**
Less than 0	None
0 to 50	Mild reaction in minority of individuals, probably not sustained
50 to 90	Stronger reaction by majority of individuals, but habituation may limit effect
90 and above	Strong avoidance reaction by virtually all individuals
Above 110	Tolerance limit of sound; unbearably loud
Above 130	Possibility of traumatic hearing damage from single event

We suggest the following criteria for noise dose for predicting and limiting deafness caused by noise.

Dose (dB_{ht}(*Species*) $L_{ep, d}$)	**Effect**
90	Limit above which hearing damage may accumulate

10 Summary and conclusions

1. The aim of the research programme was to validate the dB_{ht}(*Species*) metric as a means of objectively evaluating the effects of noise on a wide range of species. The validation has involved three different approaches.
    i. Measuring the reactions of a large number of species and individuals deflected by two acoustic guidance systems under open water conditions.
    ii. Measuring the reactions of a range of fish species with differing hearing abilities to underwater sound in a laboratory tank.
    iii. Re-interpreting public domain observations of the response of fish, marine mammals and human divers to underwater noise using the dB_{ht} metric.
2. The open water fish deflection study demonstrated a clear linear dependence for the experimental data between received dB_{ht}(*Species*) level and the response of species of fish to sound. At a received level of 82 dB_{ht}(*Clupea harengus*) 95% of herring avoided the sound. An extraplotion of the fit for other species of varying sensitivity implies that at levels of 90 dB_{ht}(*Species*) and above virtually all individuals will avoid the sound. Similarly, at levels of 10 dB_{ht}(*Species*) and below, no reaction would be expected.
3. Laboratory experiments to investigate the response of a number of species of fish to underwater sound demonstrated considerable scatter in the results. For the two species for which valid results were obtained, goldfish and pouting, there was a systematic difference in response. In general, although there was an increasing response with dB_{ht} level, much less response to the sound was measured in the laboratory tests compared with that for the fish species investigated under open water conditions. This may be due to the limited reaction opportunities in experiments of this type.
4. The laboratory measurements of the response of fish to underwater sound indicated that some fish, such as flatfish, are unsuitable as subjects. The natural behaviour of these species is to hide by staying in one position. Consequently their behaviour did not register as an avoidance response.
5. The re-interpretation of public domain literature on the response of marine mammals, fish and human divers to underwater sound supports the relationship where there is an increasing likelihood of a behavioural avoidance (aversion) response for received dB_{ht}(*Species*) levels from 55 to 90 dB_{ht}. Auditory injury occurs following prolonged exposure to levels of 90 dB_{ht} and above, with immediate auditory injury following exposures of approximately 130 dB_{ht}(*Species*). The literature indicates good agreement with the human injury model; the likelihood of injury is related to both the level of the incident sound above threshold and the duration of exposure, where the doubling of noise energy (3 dB increase) results in a halving of the acceptable exposure period (an equal energy relationship).
6. The dB_{ht} has been used in a mdel to investigate the cumulative noise exposure in marine species using the equal energy model used for human exposure to noise. This form of analysis indicates that, unless a marine mammal is within the immediate vicinity of a high level noise source and receives a noise dose causing auditory injury within the initial few minutes, the animal will flee the area before auditory injury by accumulation of noise dose occurs. A model in which an animal is exposed to noise whilst fixed in one position was considered unrealistic.
7. A set of criteria based on the use of the dB_{ht}(*Species*) is proposed that allows the likelihood of behavioural effects and damage to hearing to be assessed for a wide range of species. The metric is based on a frequency weighting system related to the hearing threshold of the species. Of significance is the conclusion that at 90 dB_{ht}(*Species*) and above there will be a

strong avoidance reaction by most individuals of that species, associated with an increasing possibility of hearing damage.

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12 Figures

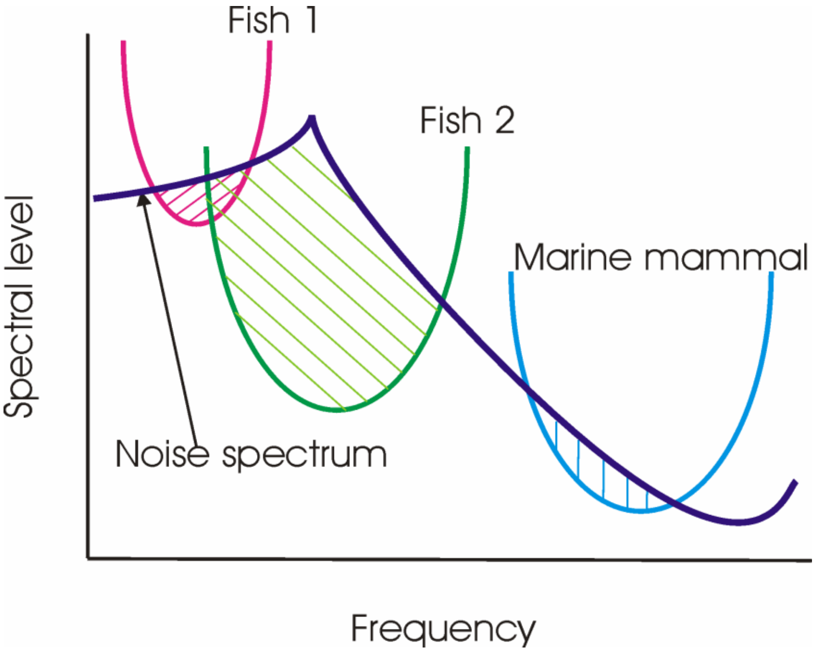

Figure 1. An idealised description of the dB_{ht} in the frequency domain

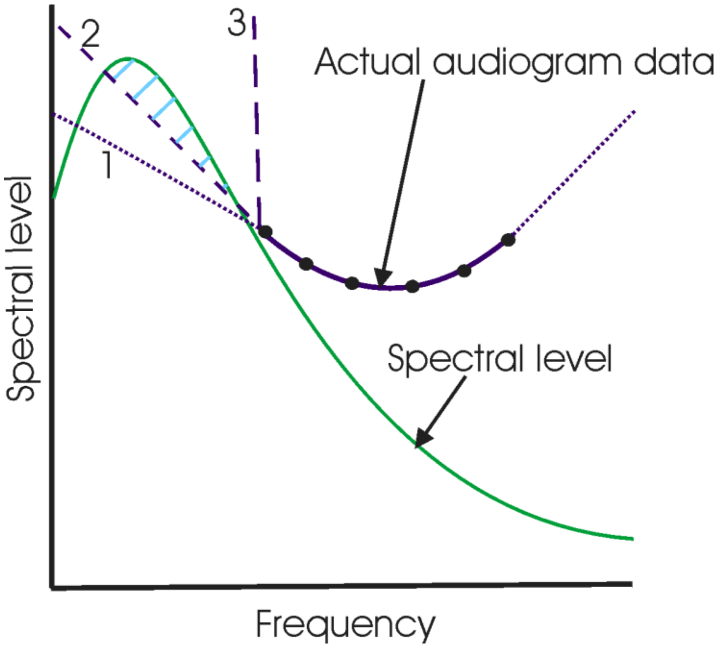

Figure 2. Illustration of inaccuracies associated with three different extrapolations of audiogram data.

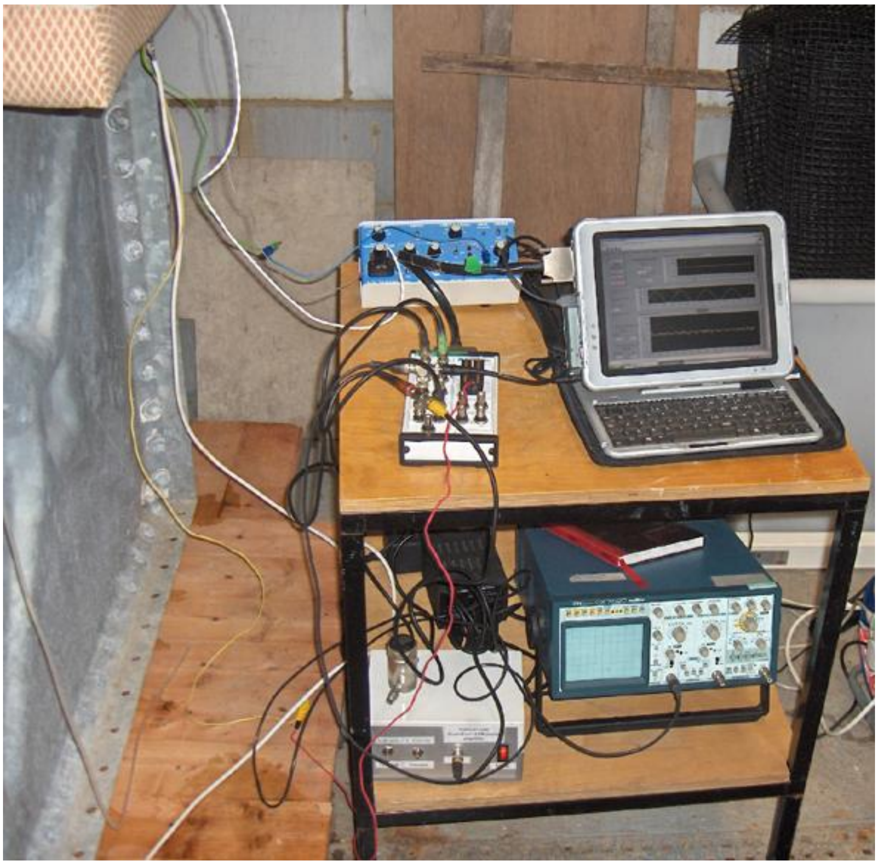

Figure 3. The experimental arrangements for ABR hearing measurements.

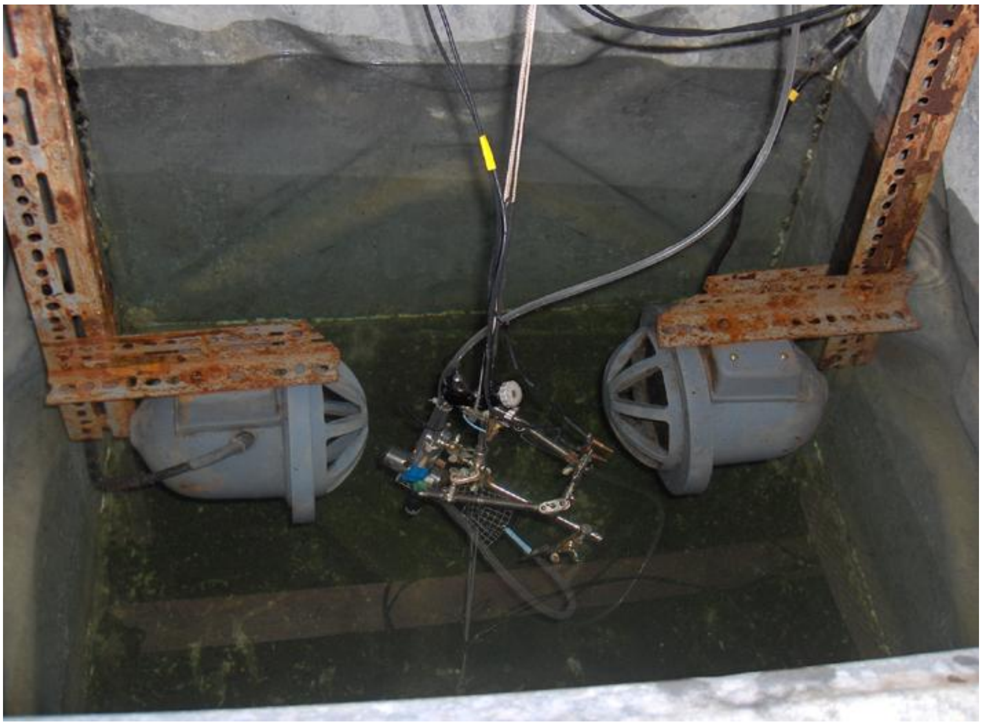

Figure 4. The cradle and electrode assembly.

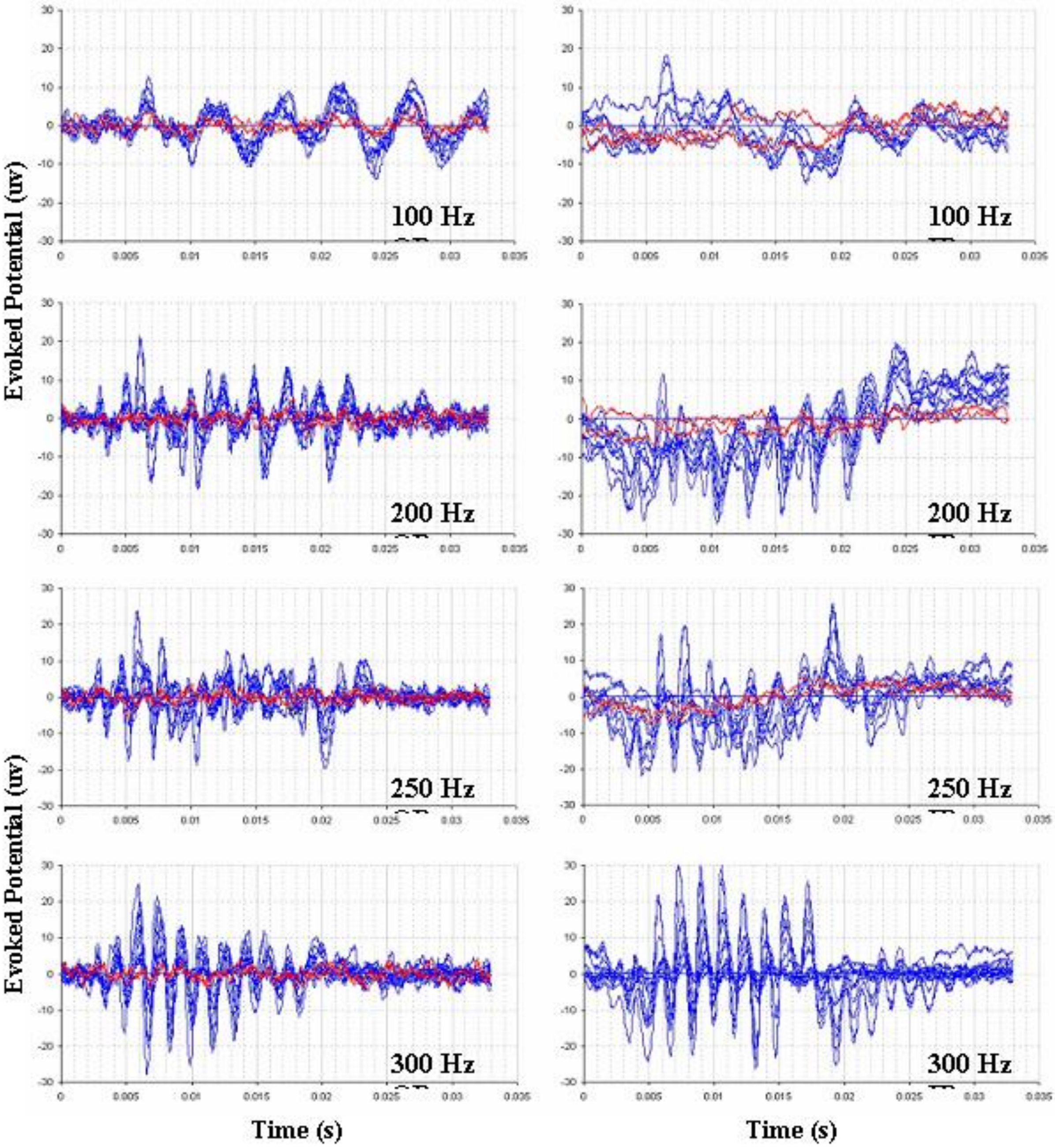

Figure 5. Evoked potentials from pouting (Trisopterus luscus) in reponse to tone bursts with the projectors driven in pressure mode in the left hand column and in particle velocity mode in the right hand column from 100 Hz to 300 Hz.

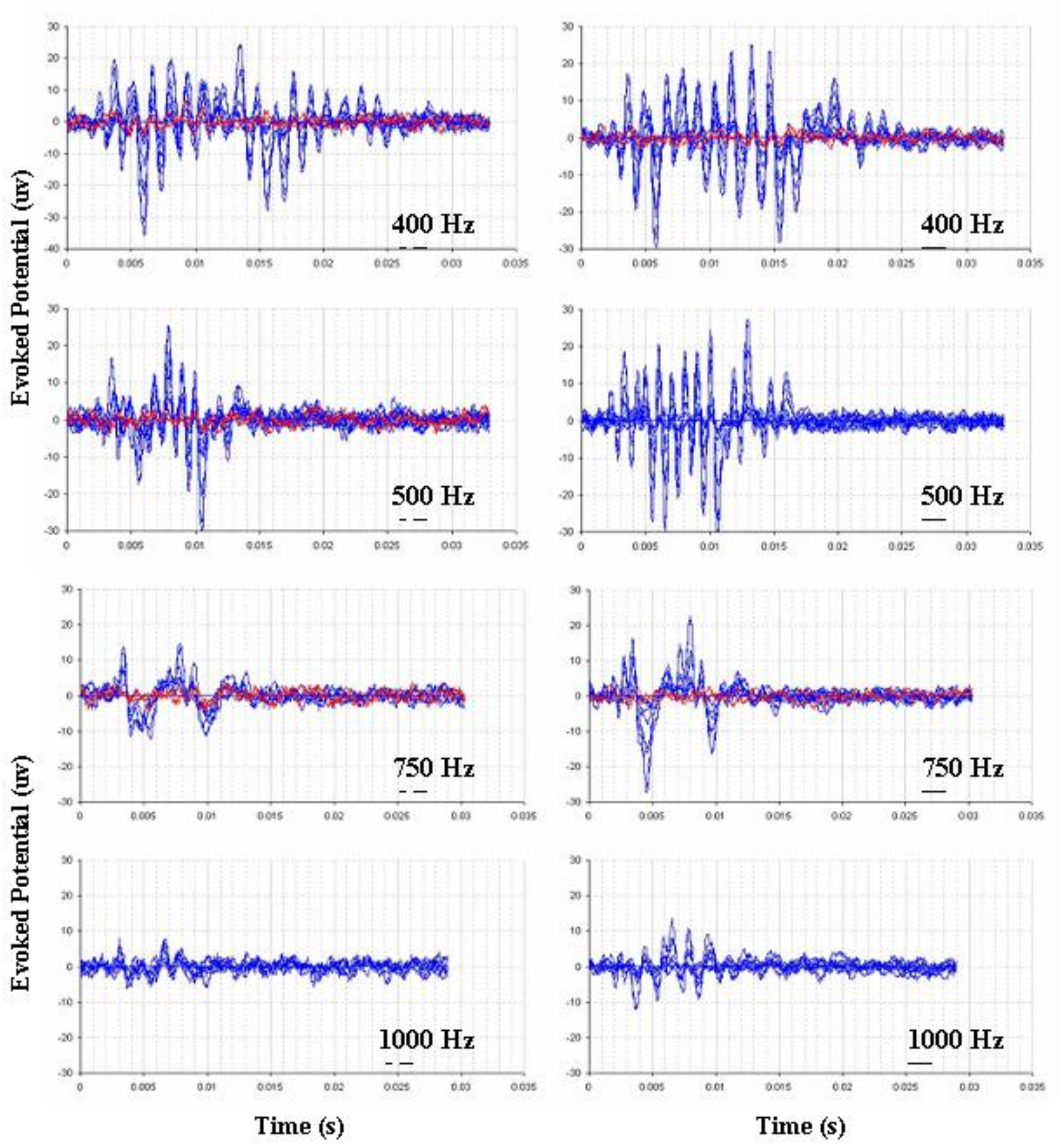

Figure 6. Evoked potentials from pouting (Trisopterus luscus) in response to tone bursts with the projectors driven in pressure mode in the left hand column and in particle velocity mode in the right hand column from 400 Hz to 1000 Hz.

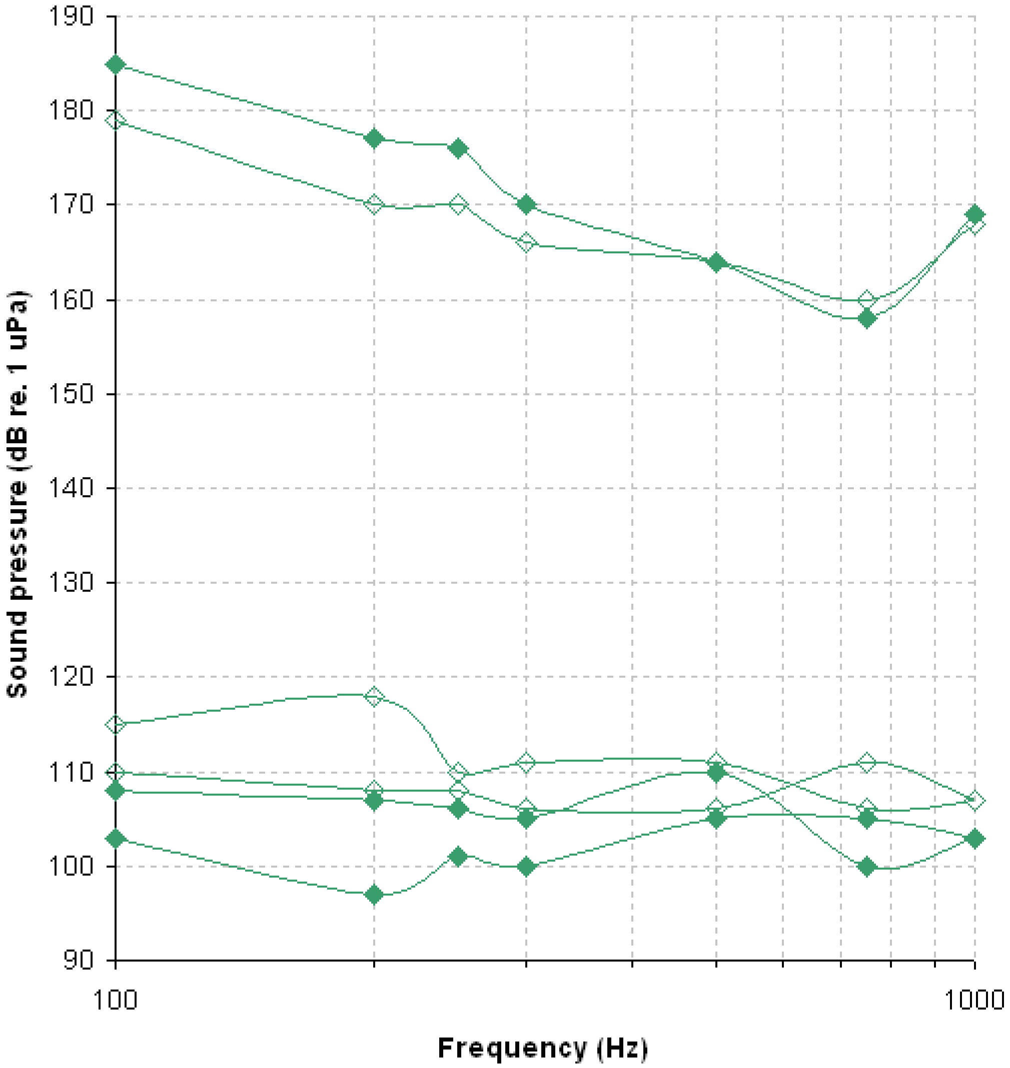

Figure 7. Audiogram for the pouting (Trisopterus luscus) calibrated for pressure (open diamonds) and particle velocity (closed diamonds) presented at frequencies ranging from 100 Hz to 1000 Hz, with the projector driven in pressure mode (lower curves) and in particle velocity mode (upper curves).

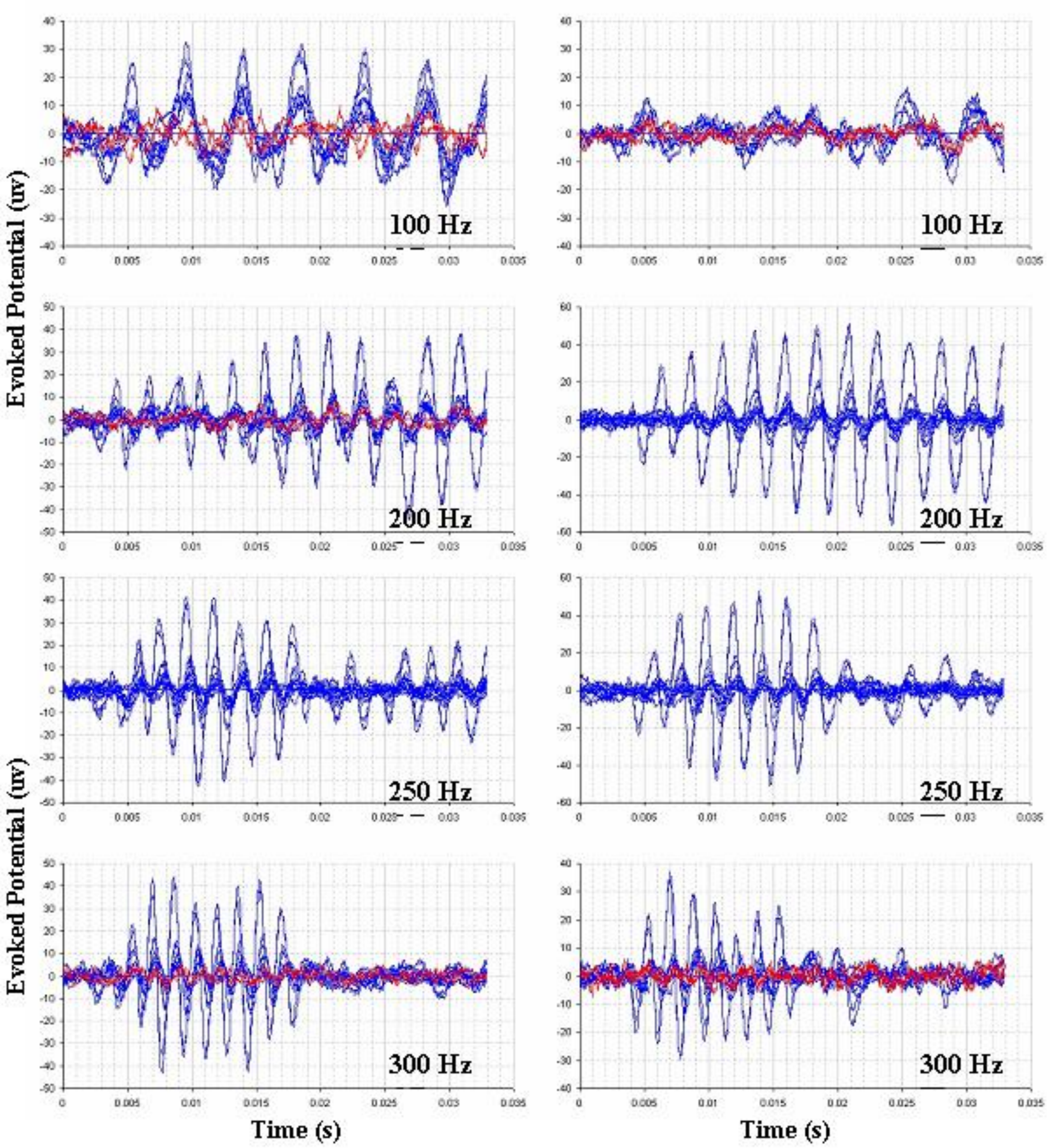

Figure 8. Evoked potentials from the sand smelt (Atherina presbyter) in response to tone bursts with the projectors driven in pressure mode in the left hand column and in particle velocity mode in the right hand column from 100 Hz to 300 Hz.

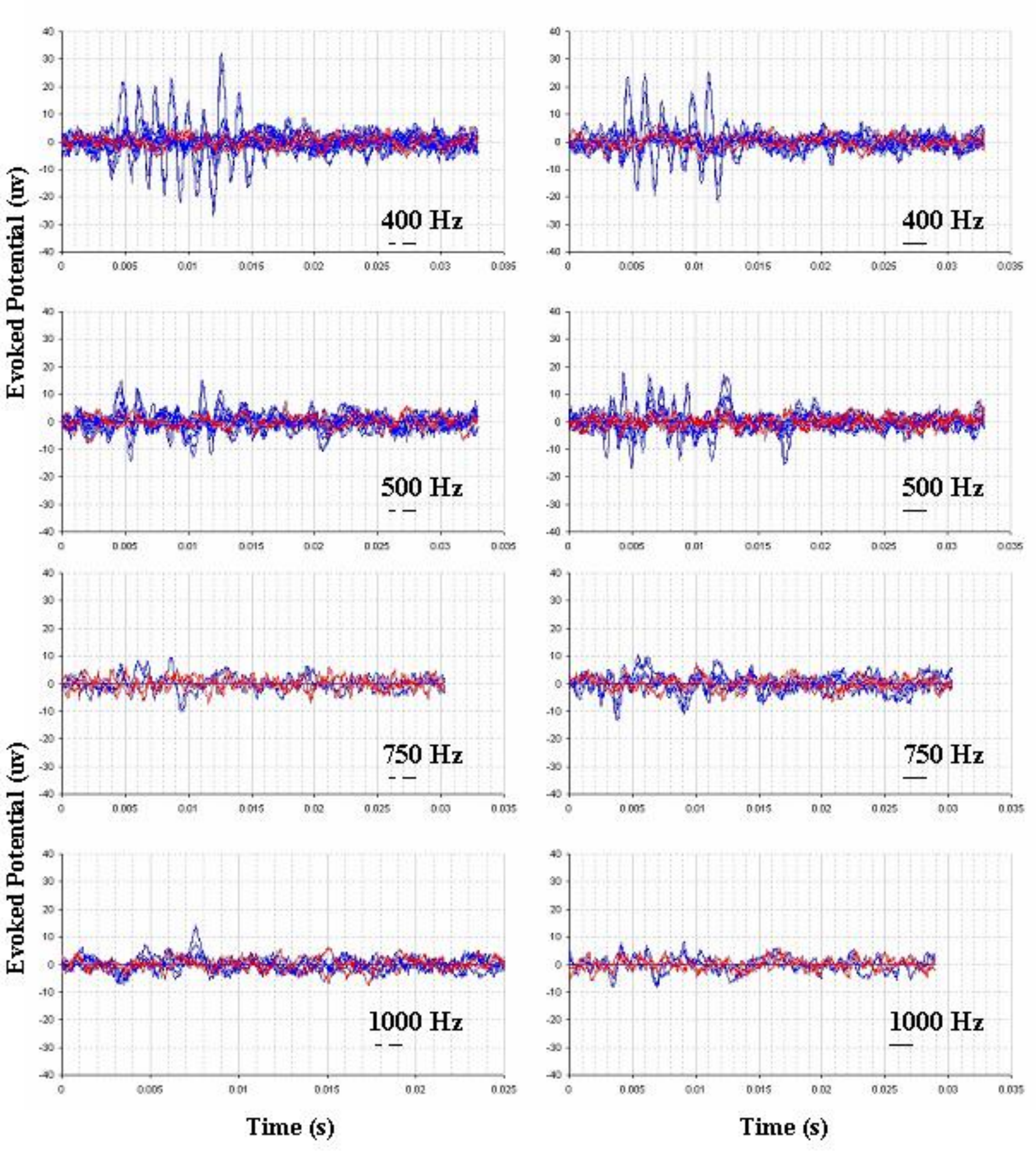

Figure 9. Evoked potentials from sand smelt (Atherina presbyter) in response to tone bursts with the projectors driven in pressure mode in the left hand column and in particle velocity mode in the right hand column from 400 Hz to 1000 Hz.

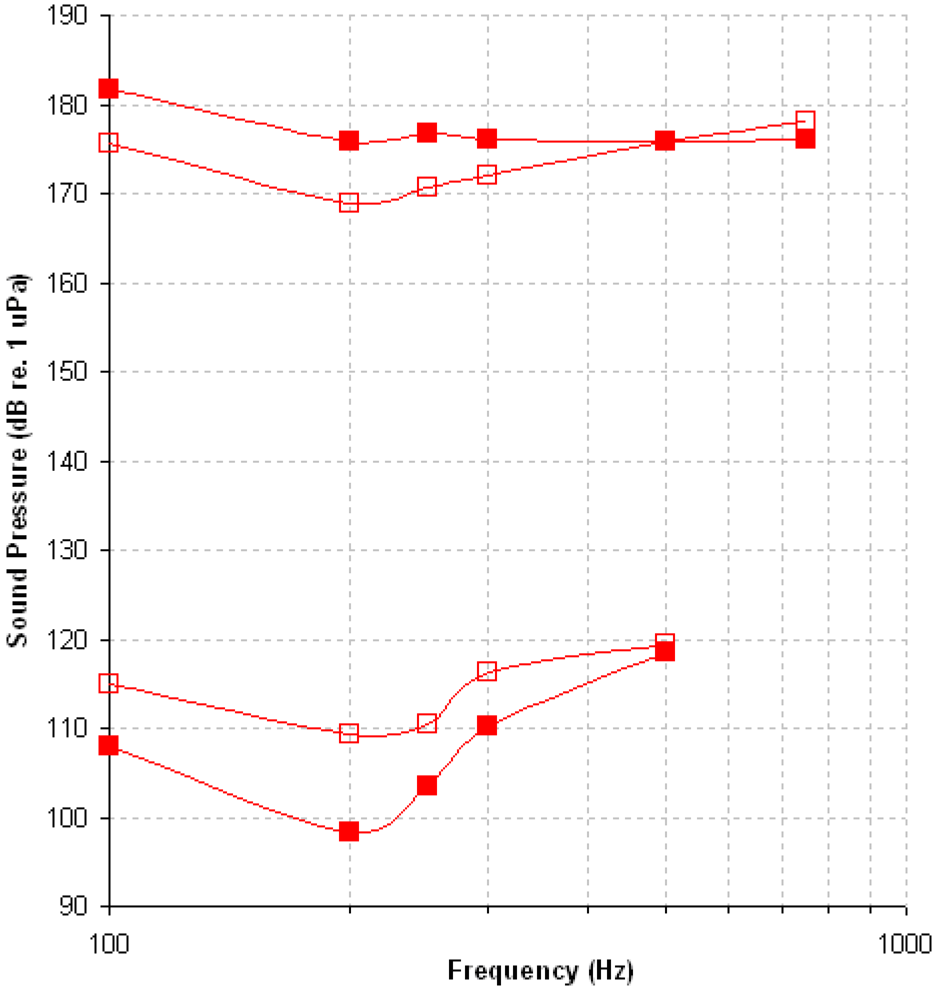

Figure 10. Average audiogram for the sand smelt (Atherina presbyter) in response to pressure (open squares) and particle velocity (closed squares) presented at frequencies ranging from 100 Hz to 1000 Hz, with the projector driven in pressure mode (lower curves) and in particle velocity mode (upper curves).

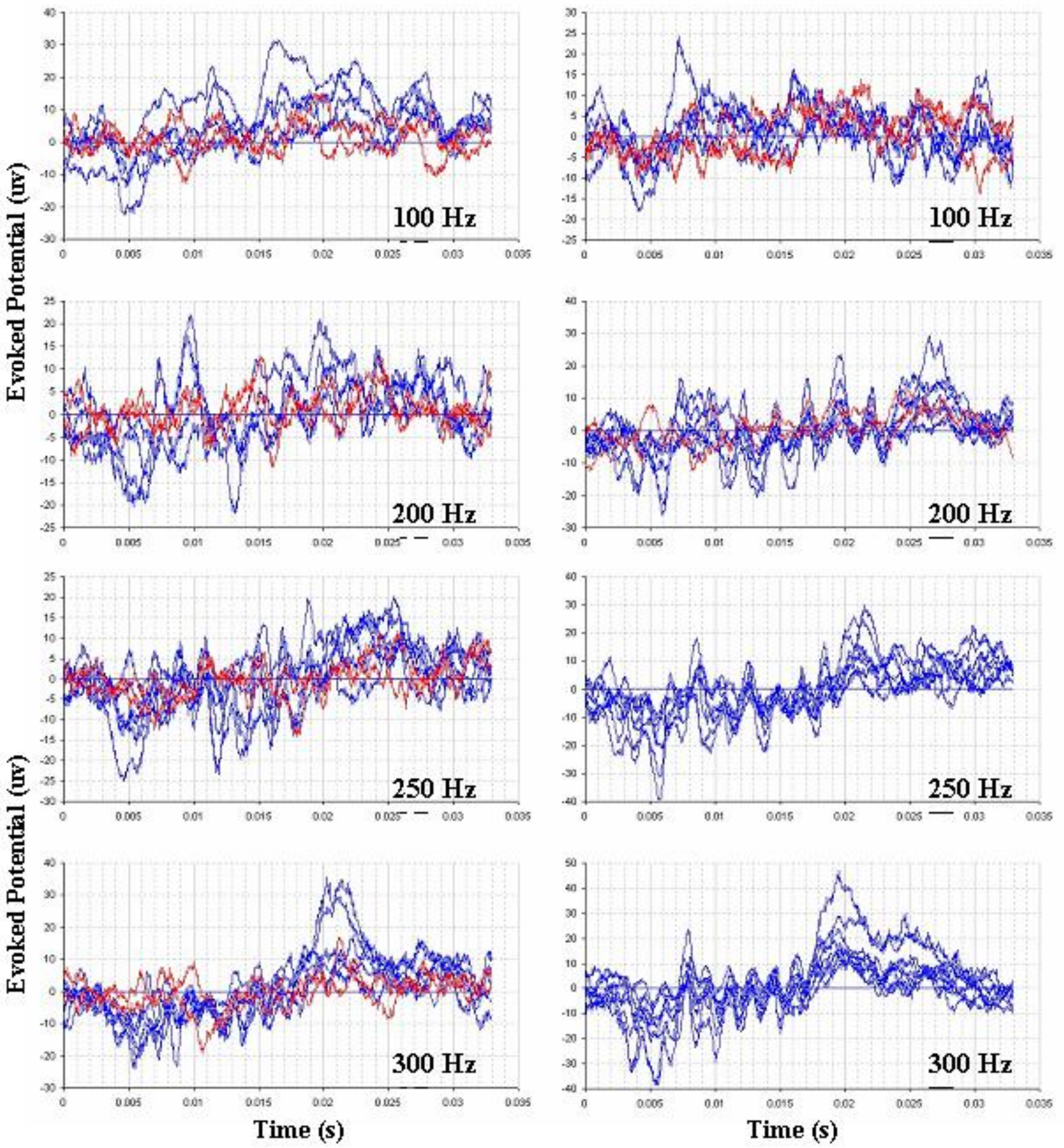

Figure 11. Evoked potentials from the salmon (Salmo salar) in response to tone bursts with the projectors driven in pressure mode in the left hand column and in particle velocity mode in the right hand column from 100 Hz to 300 Hz.

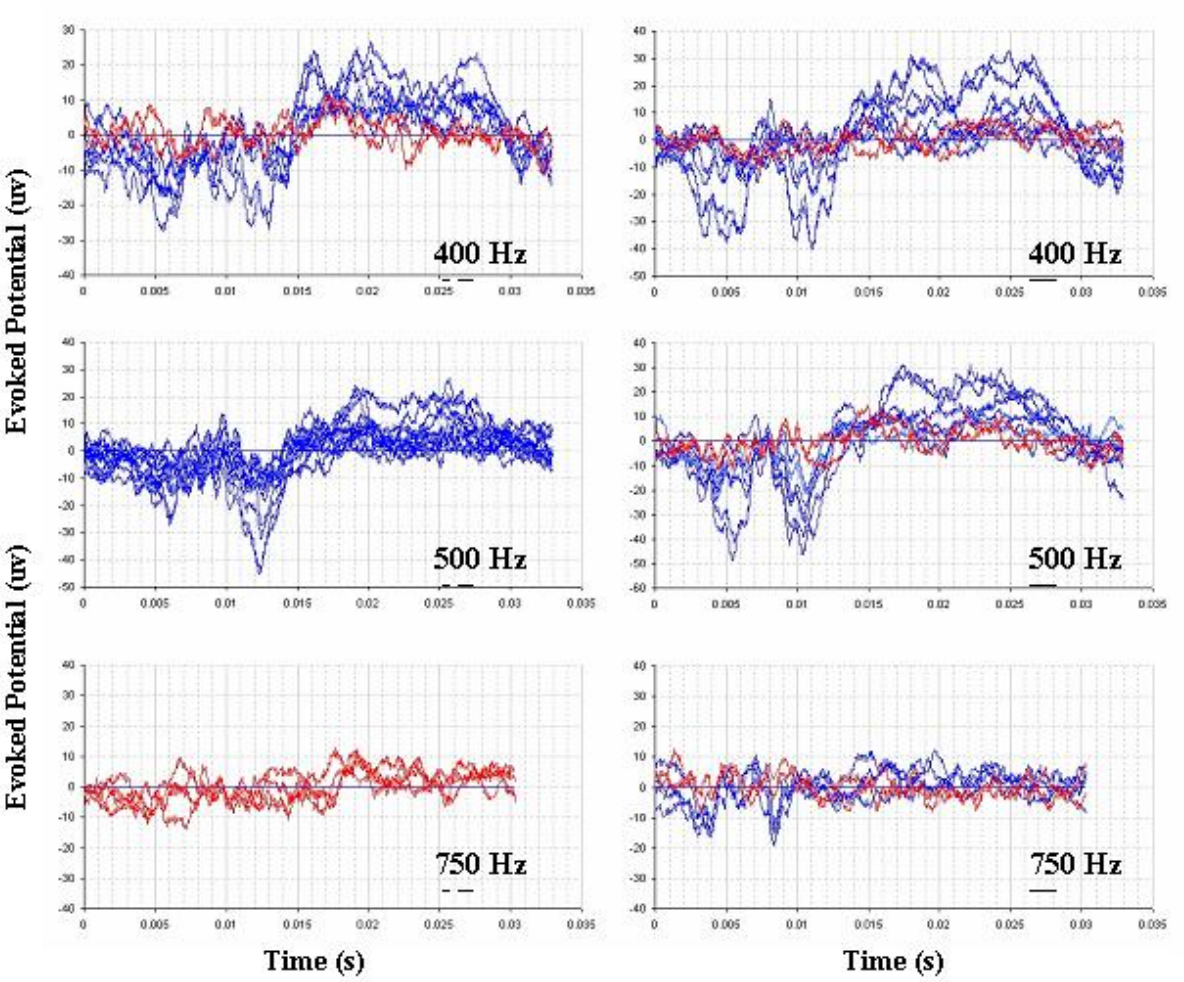

Figure 12. Evoked potentials from the salmon (Salmo salar) in response to tone bursts with the projectors driven in pressure mode in the left hand column and in particle velocity mode in the right hand column from 400 Hz to 750 Hz.

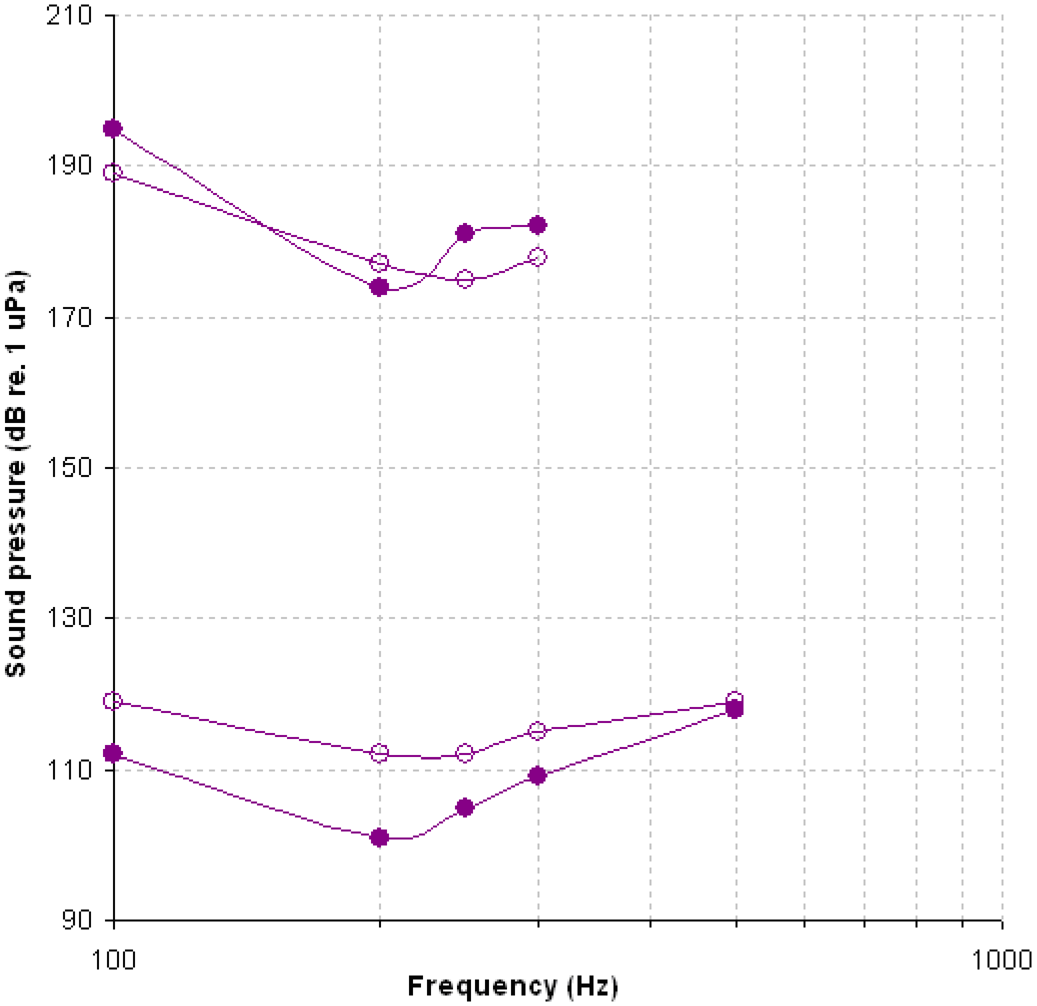

Figure 13. Audiogram for the salmon (Salmo salar) calibrated for pressure (open circles) and particle velocity (closed circles) presented at frequencies ranging from 100 Hz, with the projector driven in pressure mode (lower curves) and in particle velocity mode (upper curves).

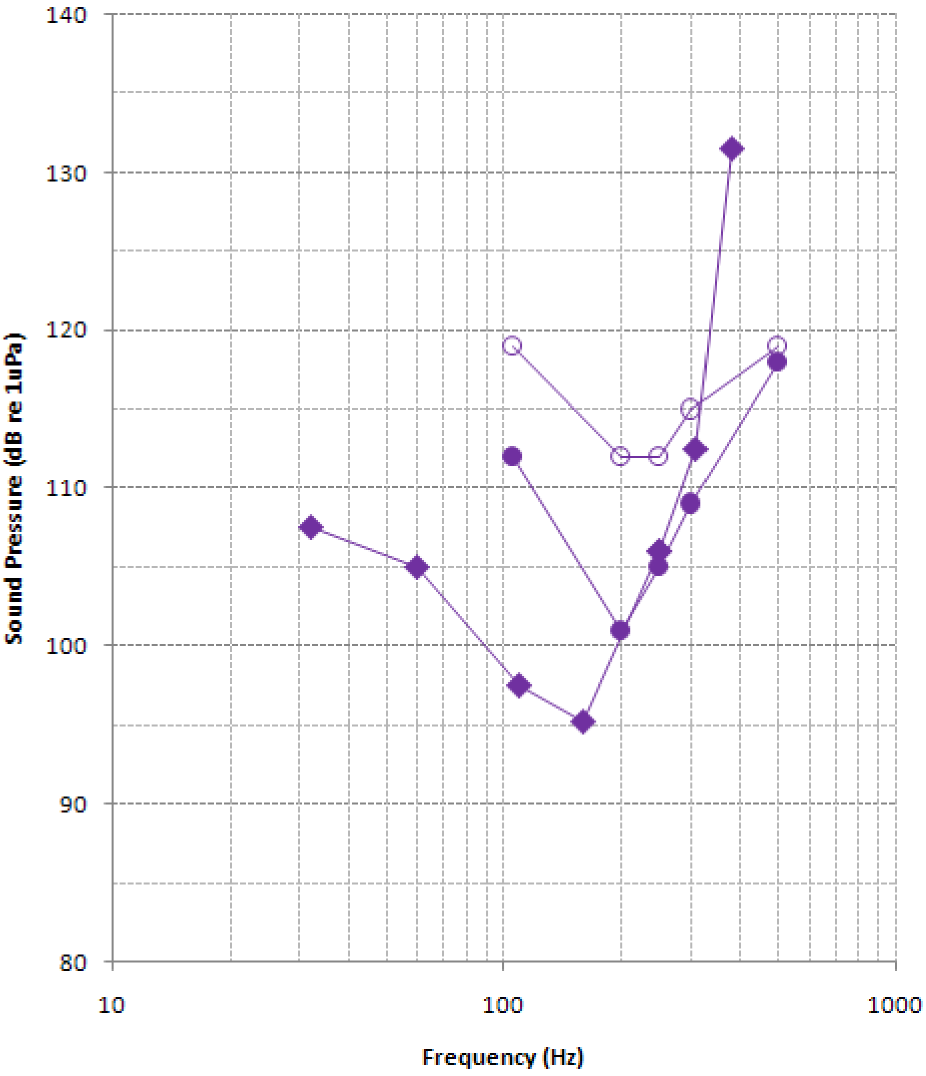

Figure 14. The ABR audiogram for salmon calibrated in pressure (open circles), particle velocity (closed circles) and the behavioural audiogram from Hawkins & Johnstone (1978) (closed diamonds).

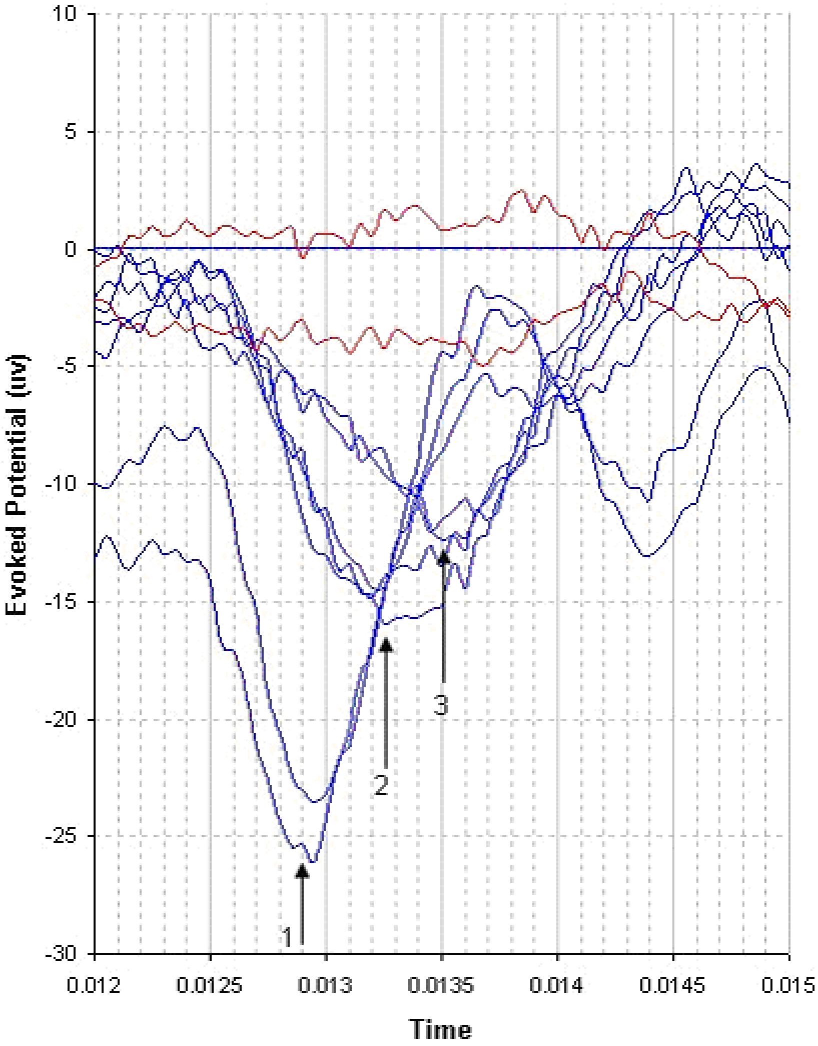

Figure 15. Inter Peak Latency (IPL) of the ABR response from pouting (T. luscus) to the particle velocity component of a 200 Hz tone burst, attenuated in 5 dB steps.

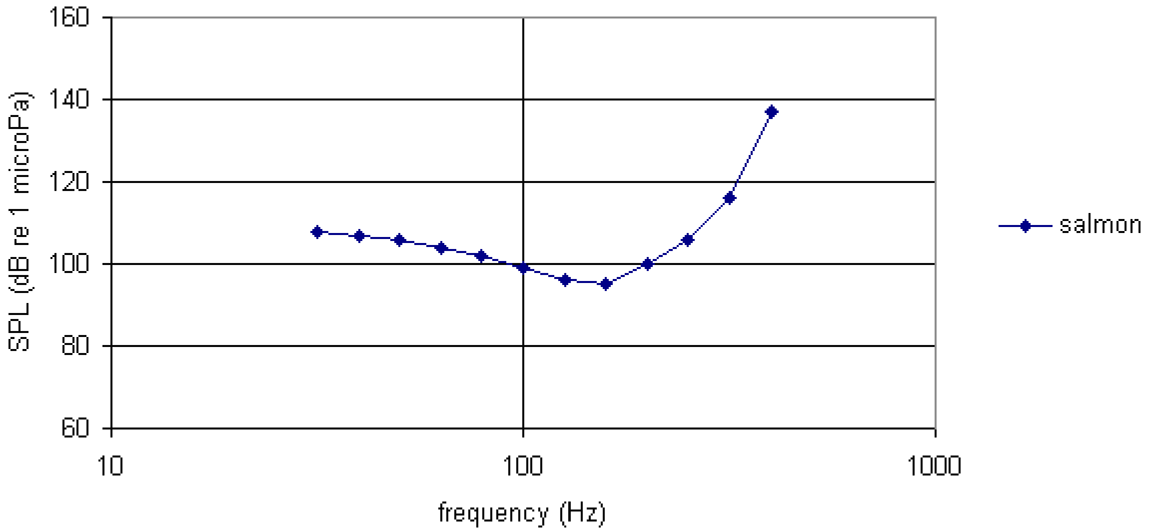

Figure 16. A representation of the salmon audiogram selected for the FIR filter model (based on the salmon audiogram of Hawkins & Johnstone (1978)).

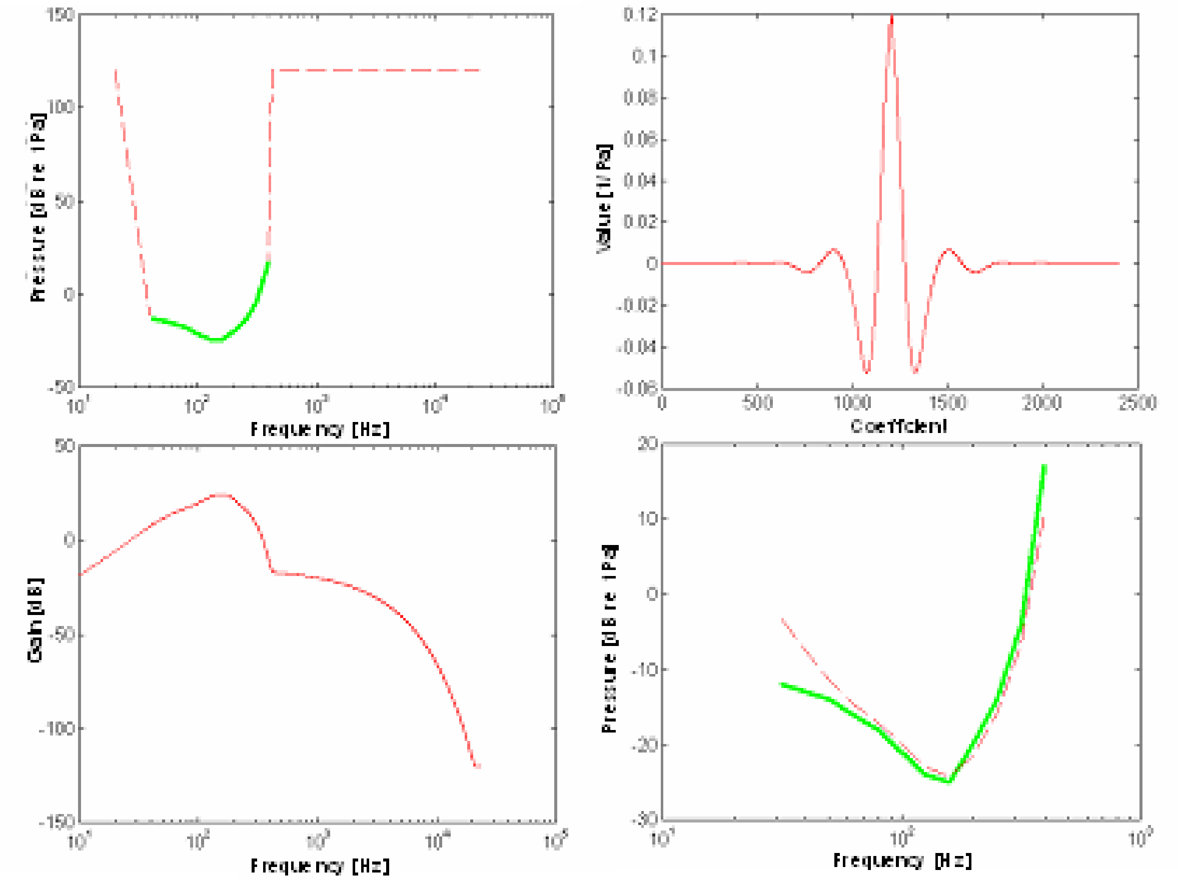

Figure 17 (a) (b) (c) (d). The behaviour of the dB$_{ht}$(Salmo salar) filter; (a) Ideal frequency response (dashed) and measured thresholds (solid); (b) Filter impulse response; (c) Filter frequency response; (d) Comparison of audiogram (solid) with dB$_{ht}$(Salmo salar) weighted threshold level tones (dashed).

Figure 18. The Doel nuclear power station, Belgium.

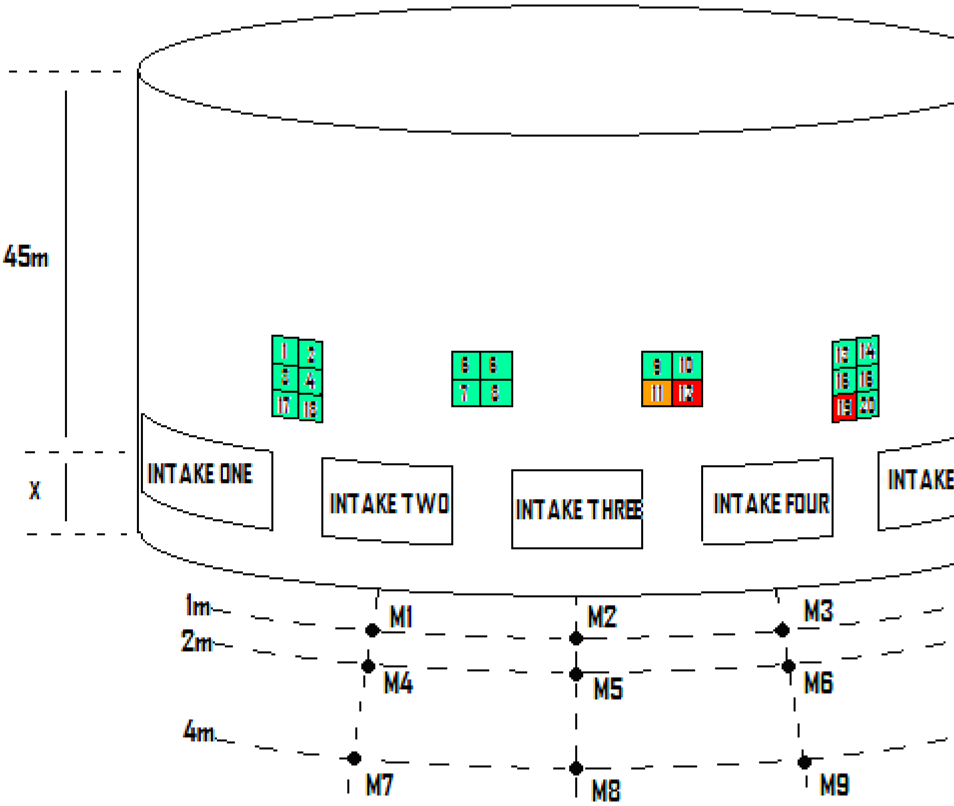

Figure 19. The cooling water intake structure and measurement positions.

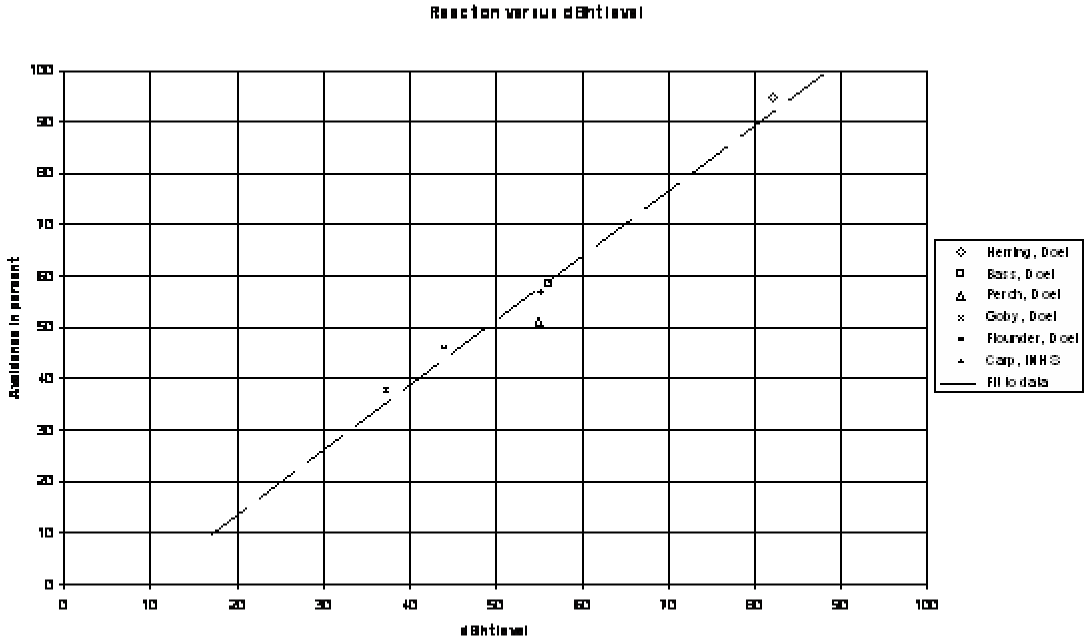

Figure 20. The efficiency of the Doel and INHS acoustic fish deflection systems vs the level of sound in dB_{ht} units.

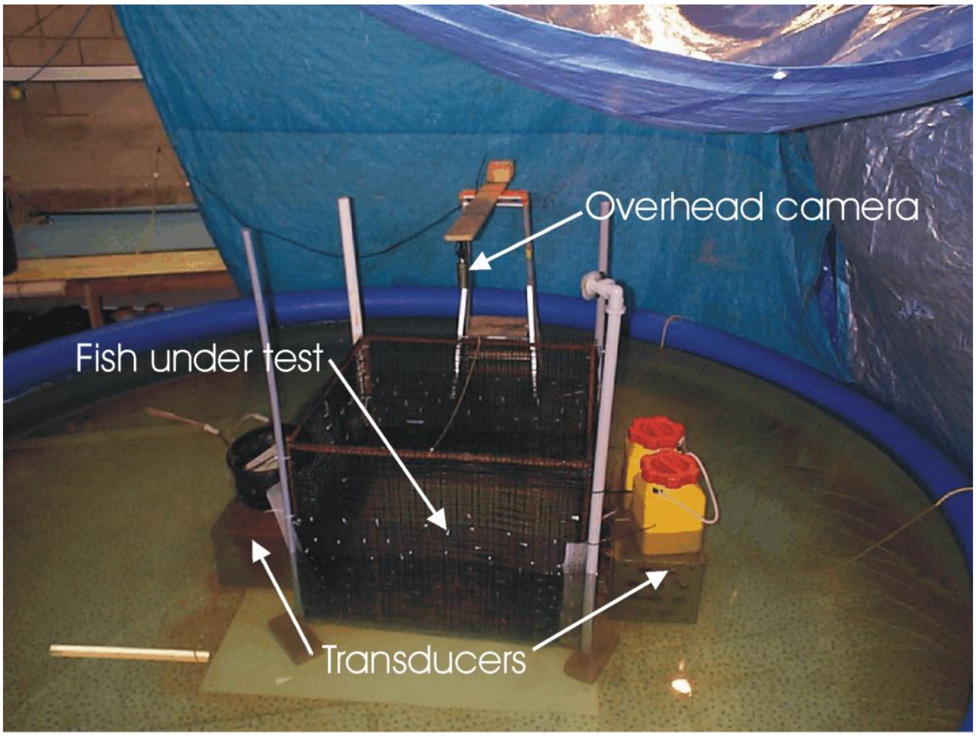

Figure 21. The reaction tests experimental setup, showing test cage, sound projector and overhead camera in test pool.

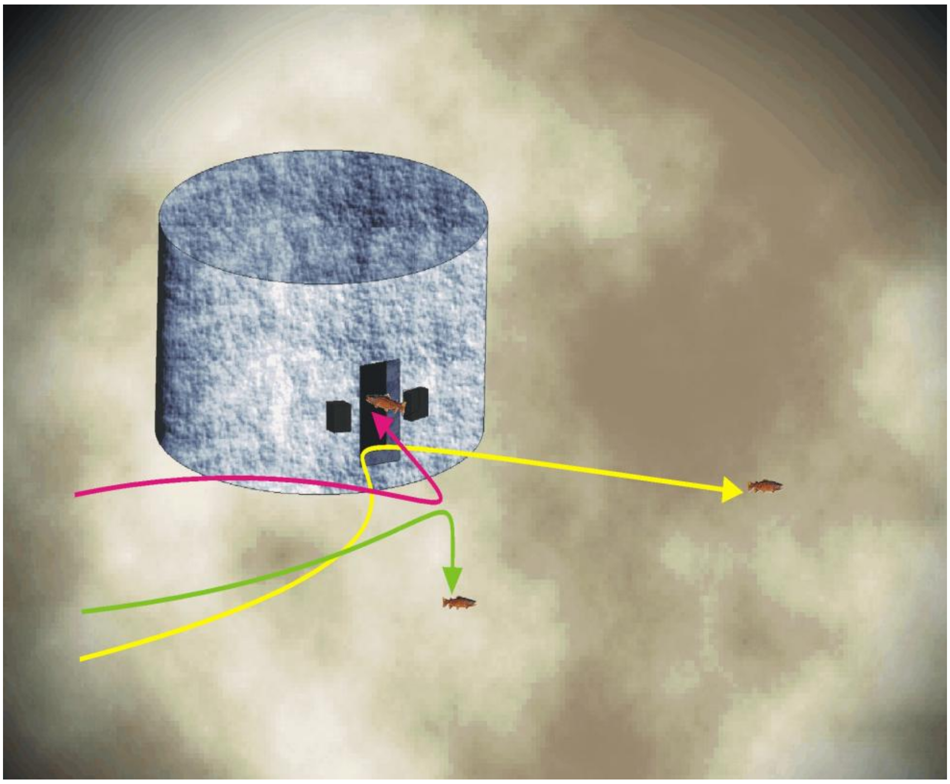

Figure 22. An illustration of a cooling water inlet at Doel, indicating the three reactions (entry, avoidance and staying in place) that can result when an individual approaches.

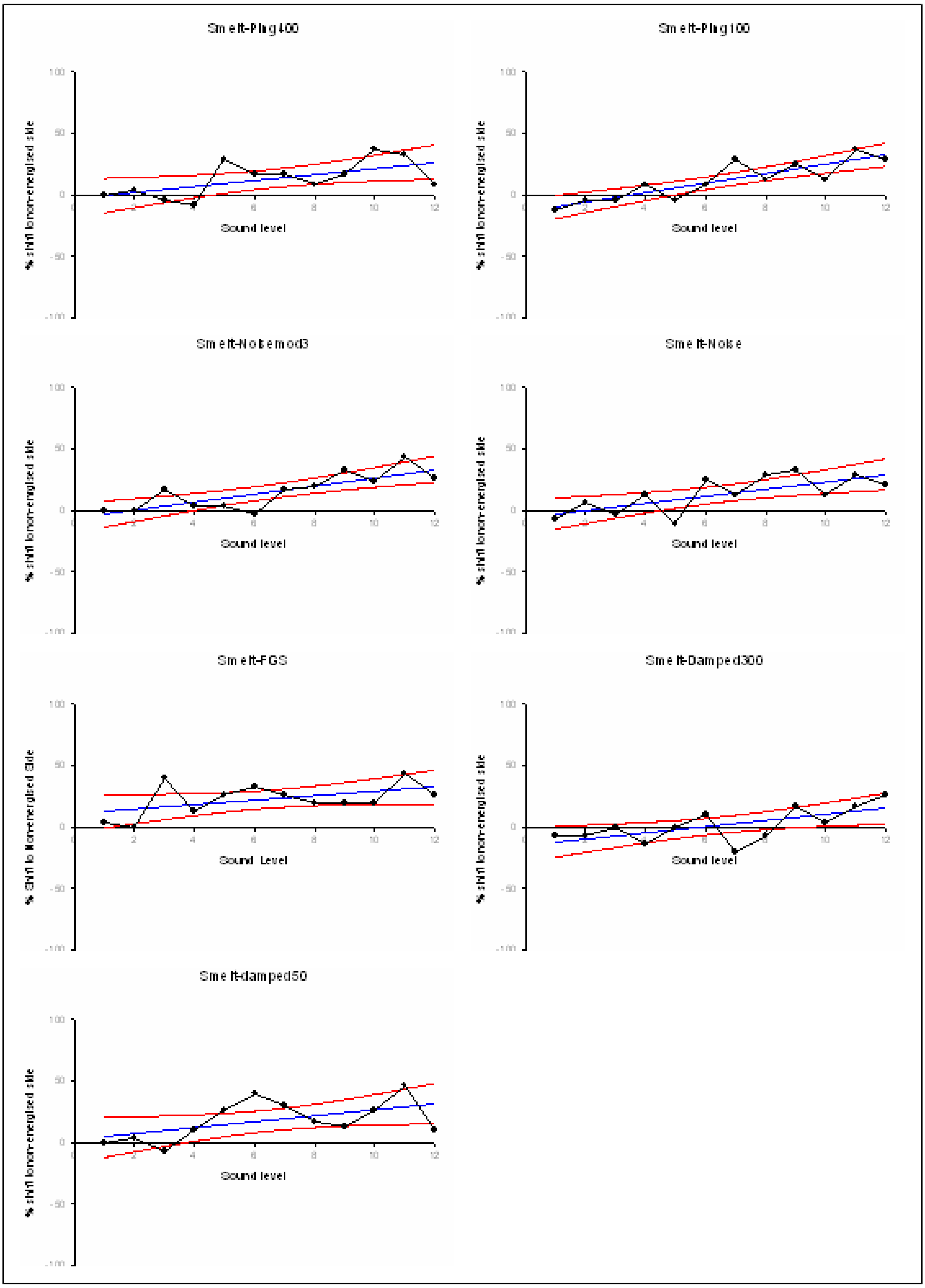

Figure 23. A typical set of unprocessed results for the reaction tests for smelt, showing the percentage of fish avoiding the sound vs the level of the sound.

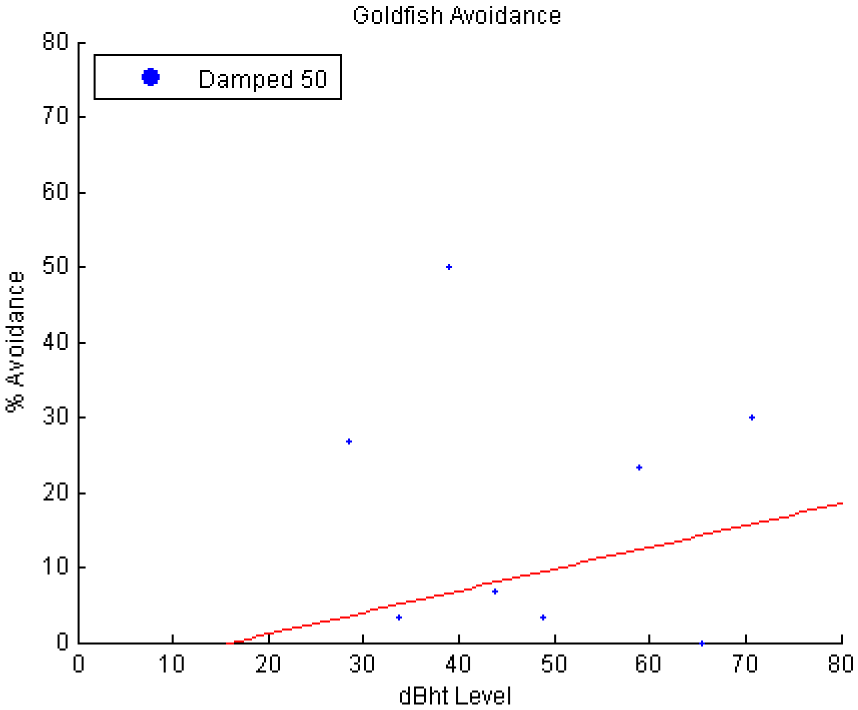

Figure 24. Avoidance results for the goldfish, for the damped 50 Hz sinewave, showing the percentage of fish avoiding the sound vs the level of the sound.

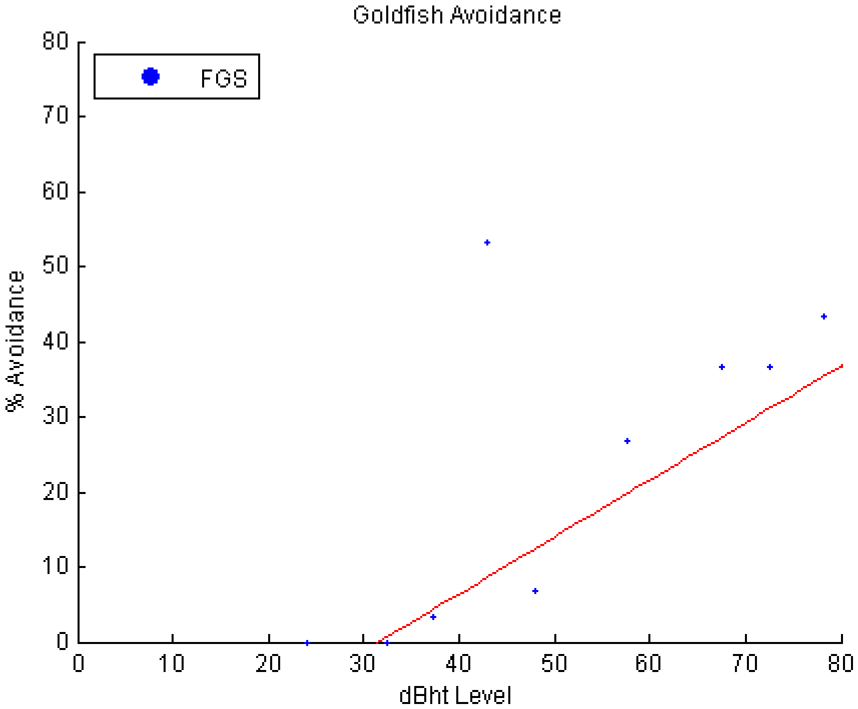

Figure 25. Avoidance results for the goldfish, for the swept sinewave, showing the percentage of fish avoiding the sound vs the level of the sound.

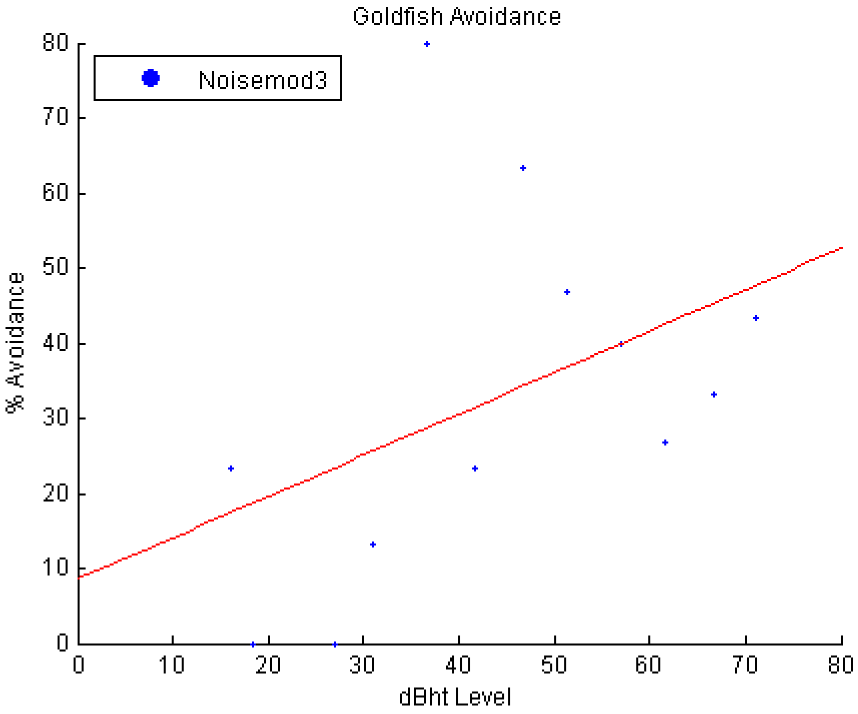

Figure 26. Avoidance results for the goldfish, for modulated white noise, showing the percentage of fish avoiding the sound vs the level of the sound.

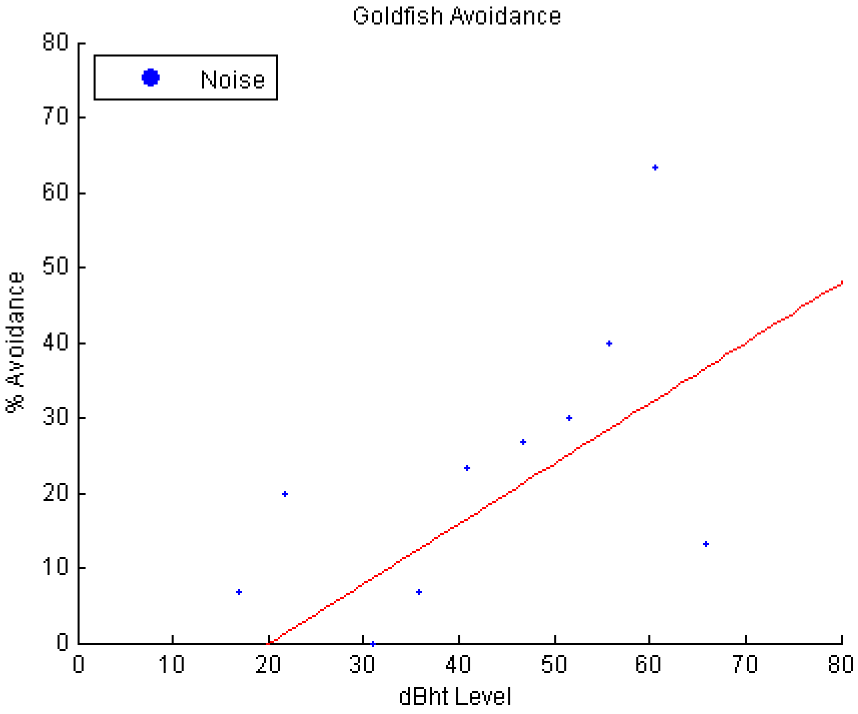

Figure 27. Avoidance results for the goldfish, for white noise, showing the percentage of fish avoiding the sound vs the level of the sound.

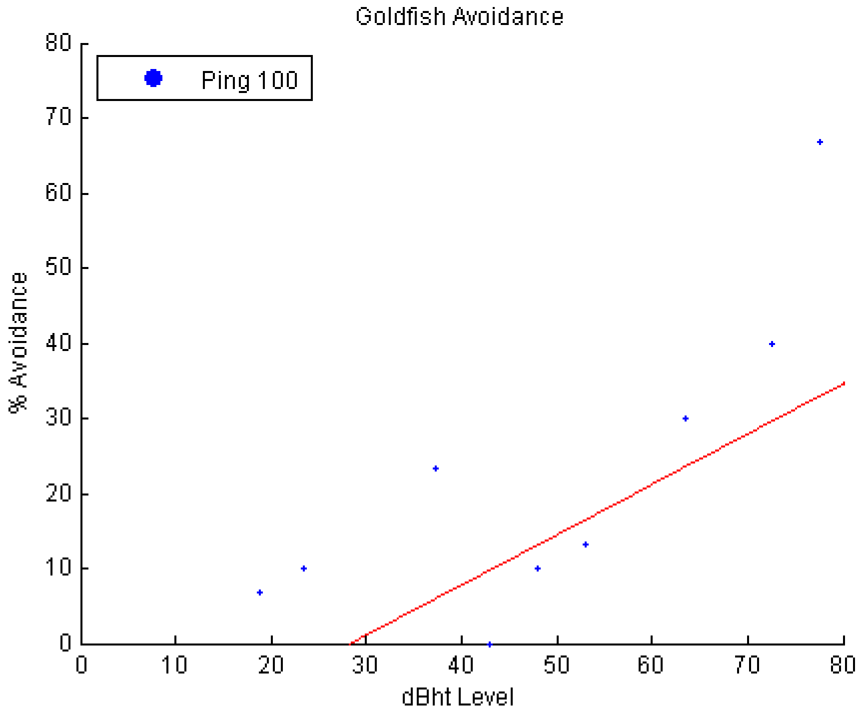

Figure 28. Avoidance results for the goldfish, for a 100 Hz ping, showing the percentage of fish avoiding the sound vs the level of the sound.

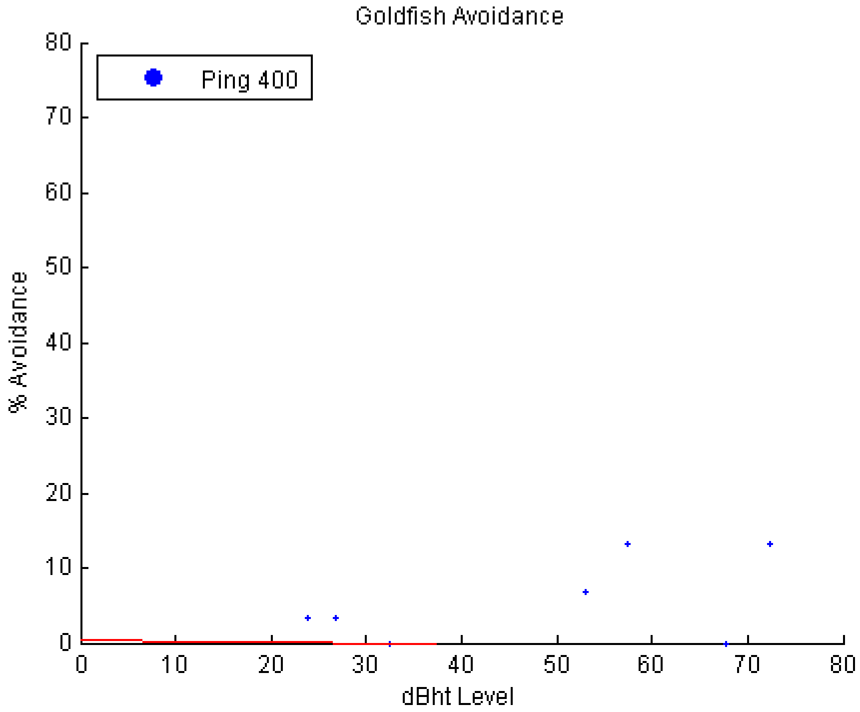

Figure 29. Avoidance results for the goldfish, for a 400 Hz ping, showing the percentage of fish avoiding the sound vs the level of the sound.

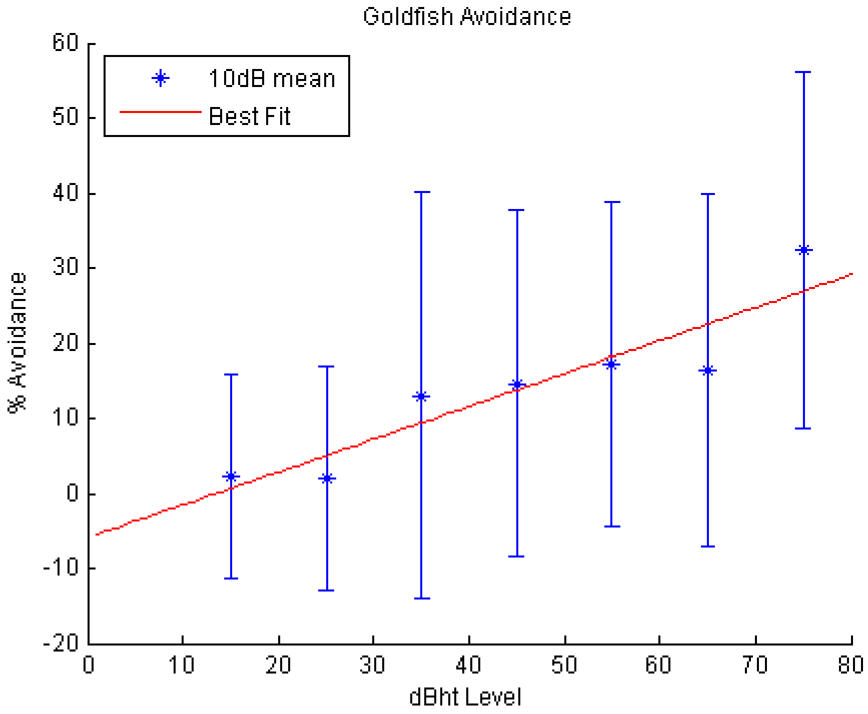

Figure 30. Avoidance results for the goldfish, averaged over all sounds and over 10 dB bins.

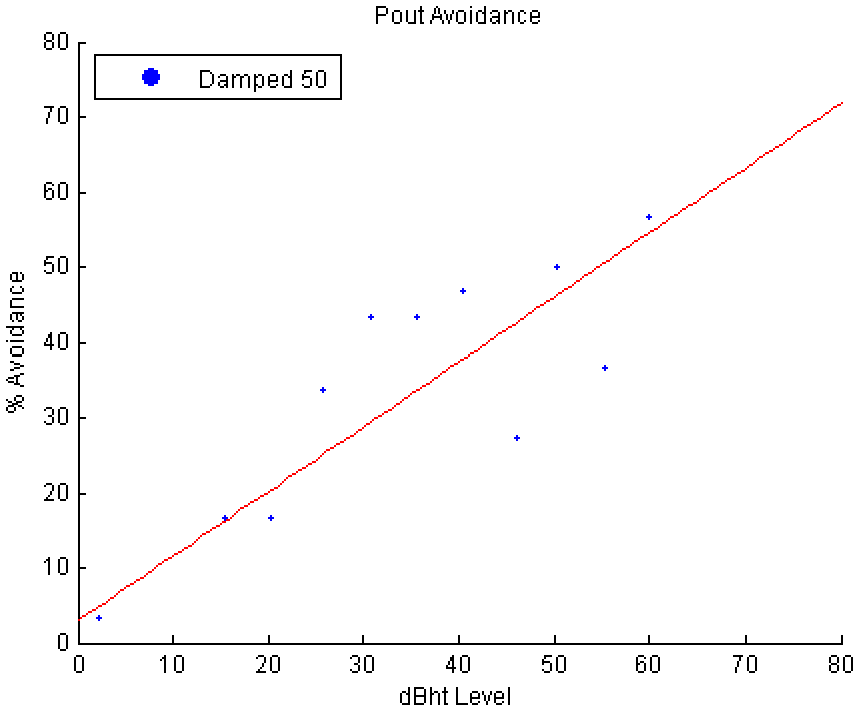

Figure 31. Avoidance results for the pouting, for the damped 50 Hz sinewave, showing the percentage of fish avoiding the sound vs the level of the sound.

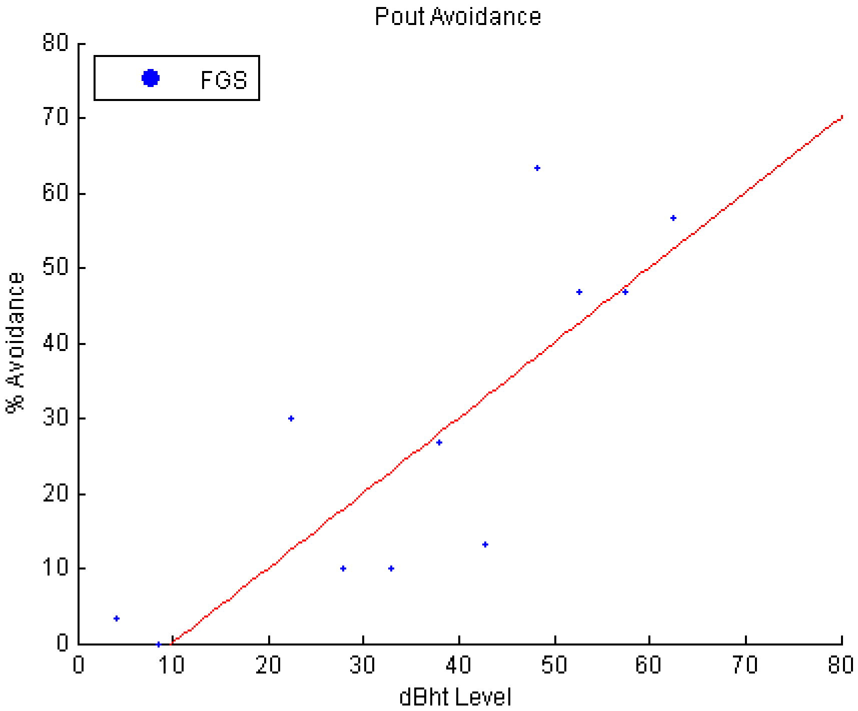

Figure 32. Avoidance results for the pouting, for the swept sinewave, showing the percentage of fish avoiding the sound vs the level of the sound.

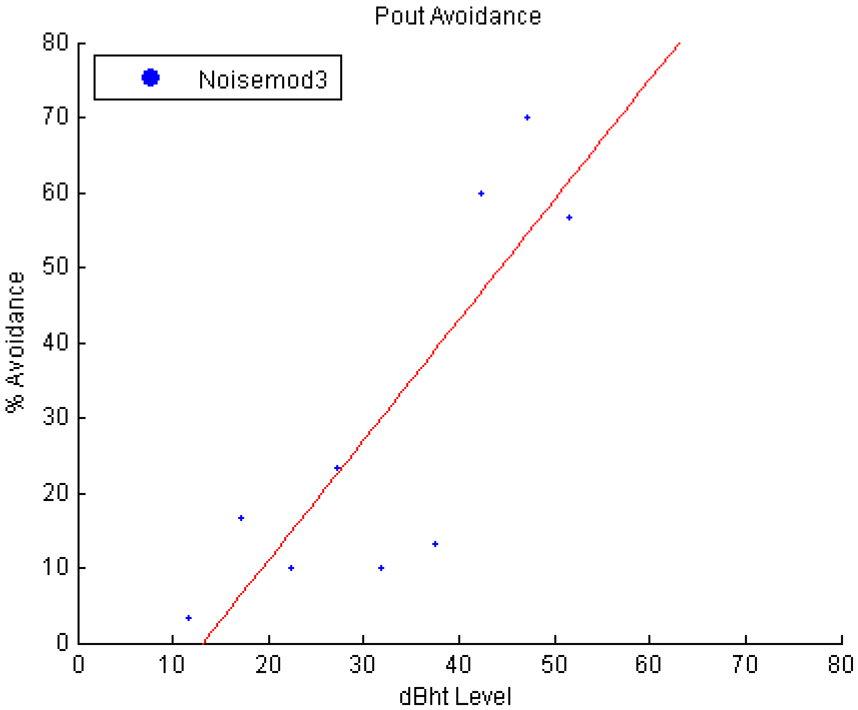

Figure 33. Avoidance results for the pouting, for modulated noise, showing the percentage of fish avoiding the sound vs the level of the sound.

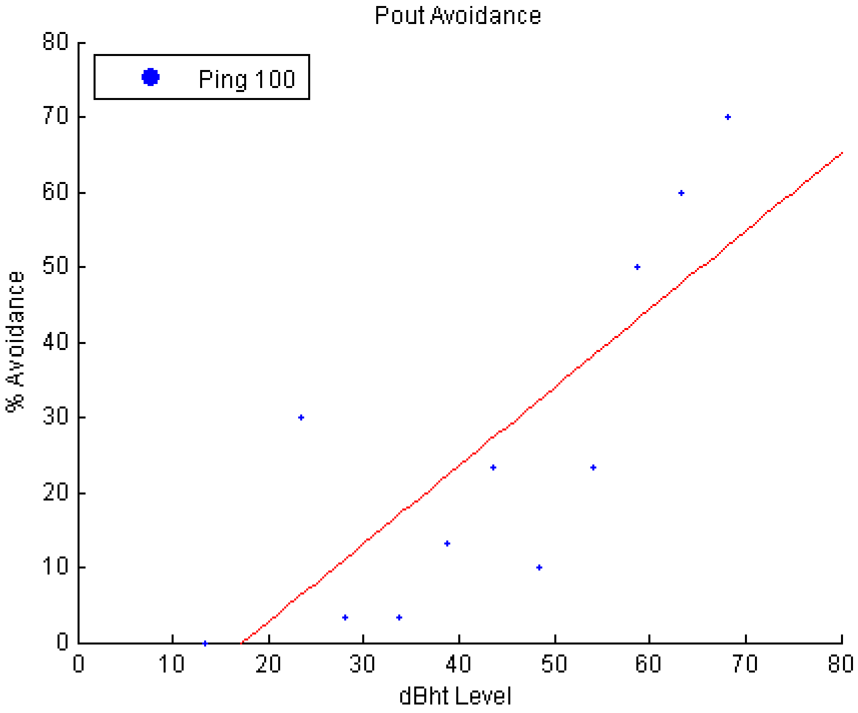

Figure 34. Avoidance results for the pouting, for the 100 Hz ping, showing the percentage of fish avoiding the sound vs the level of the sound.

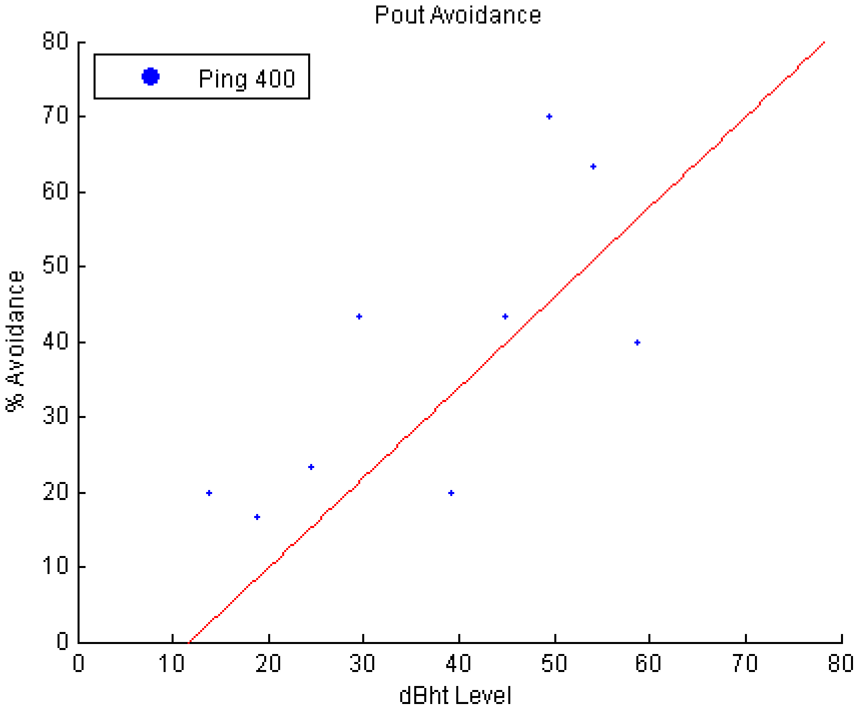

Figure 35. Avoidance results for the pouting, for the 400 Hz sinewave, showing the percentage of fish avoiding the sound vs the level of the sound.

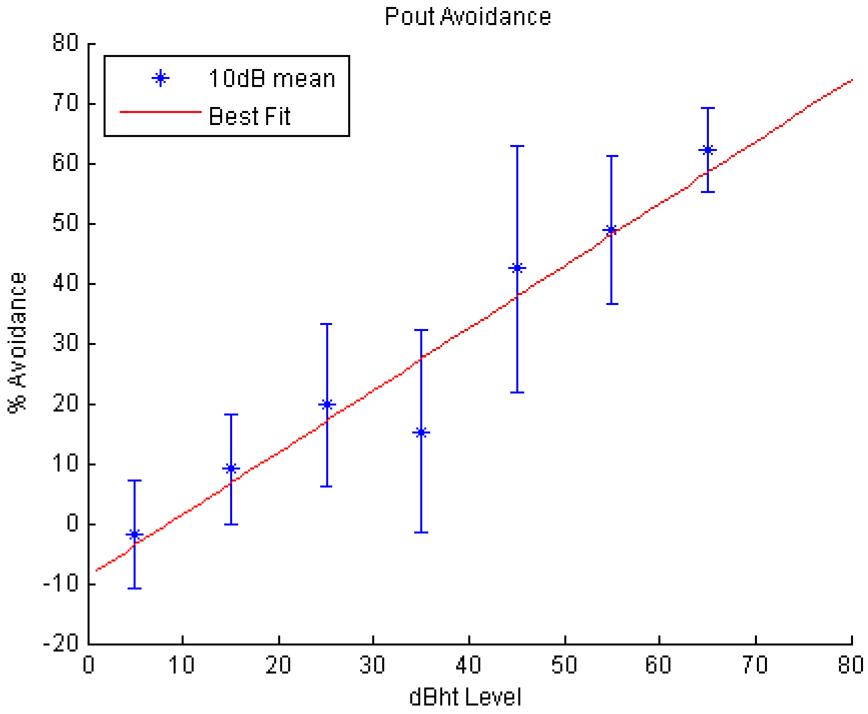

Figure 36. Avoidance results for the pouting, averaged over all sounds and over 10 dB bins.

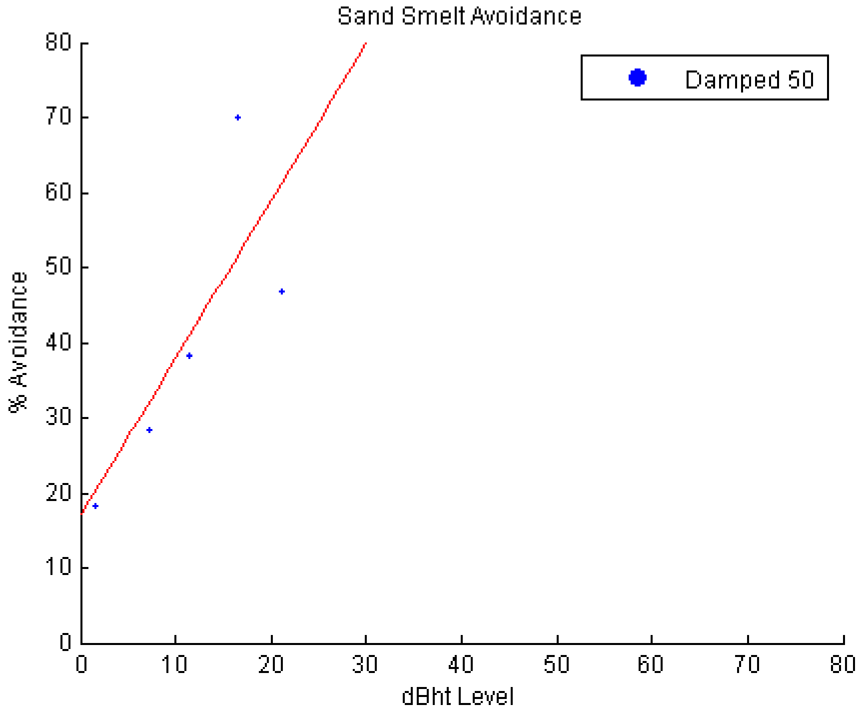

Figure 37. Avoidance results for the sand smelt, for the damped 50 Hz sinewave, indicating limited range of data.

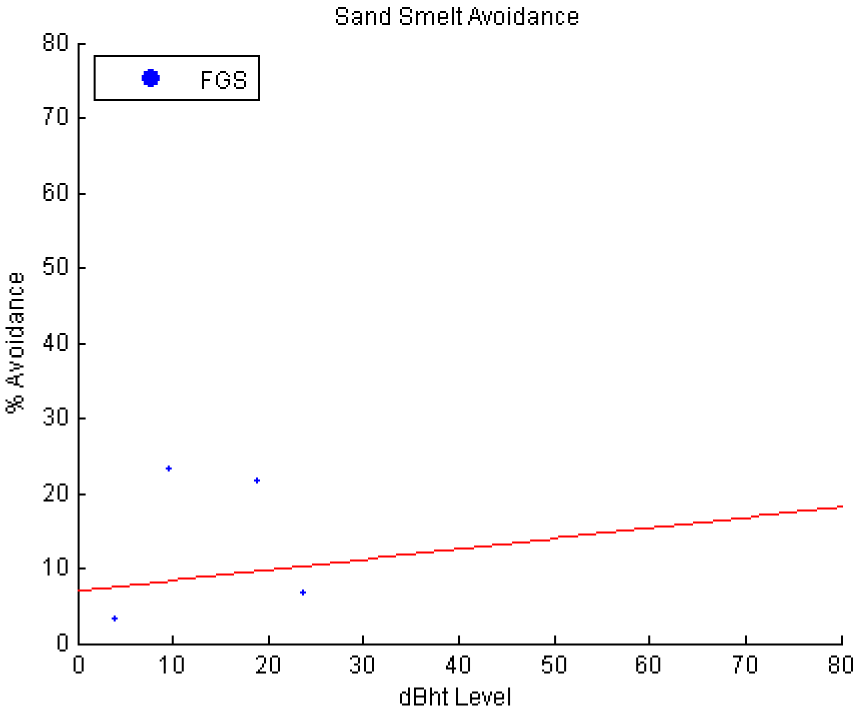

Figure 38. Avoidance results for the sand smelt, for the swept sinewave, indicating limited range of data.

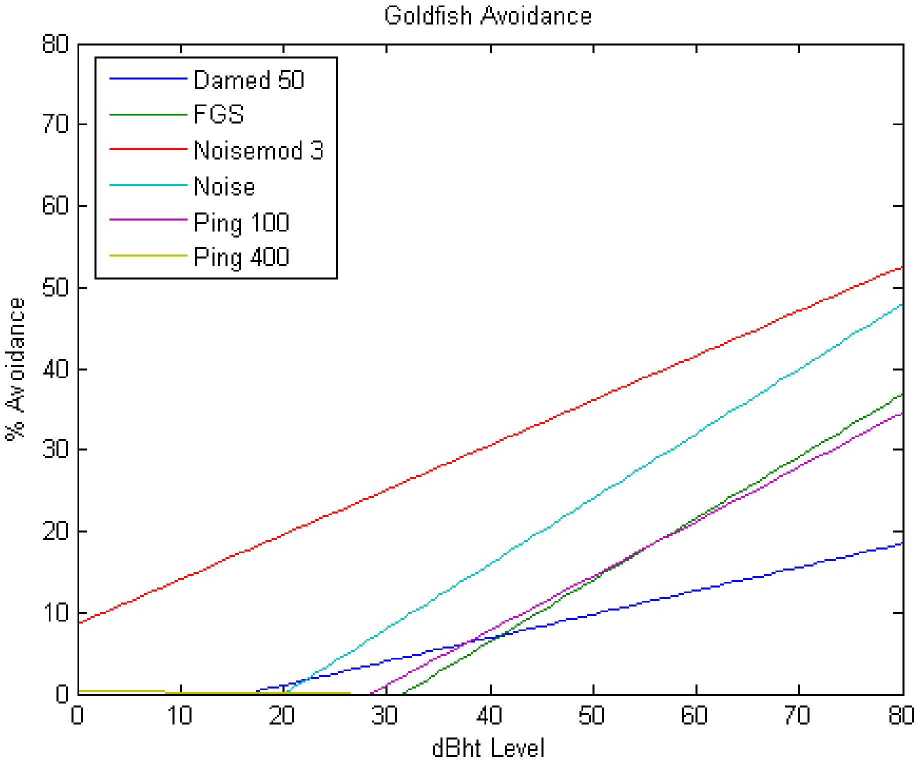

Figure 39. Summary of data for the goldfish: The best fits of the reaction tests for the various sounds.

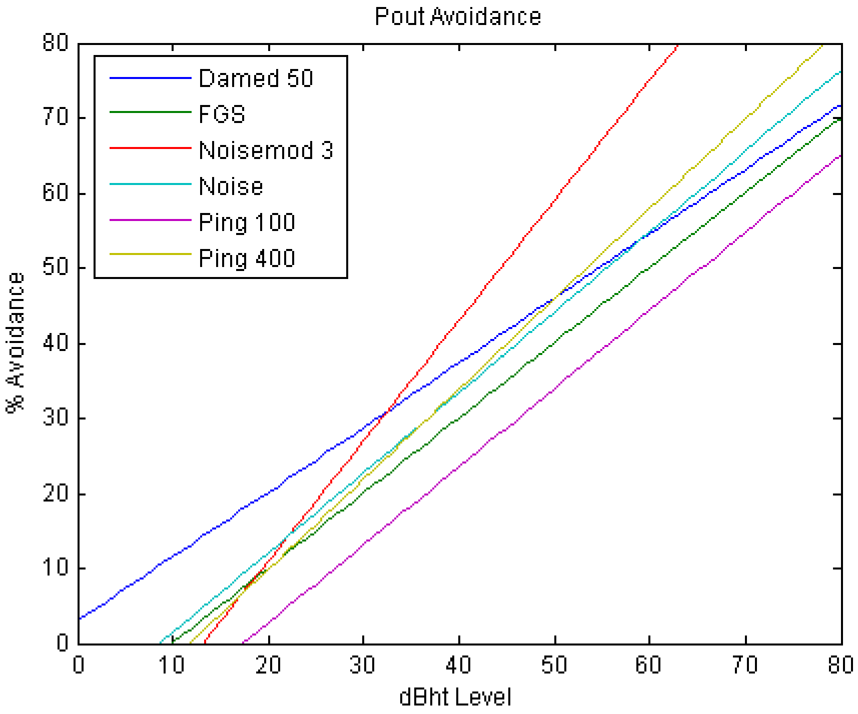

Figure 40. Summary of data for the pouting: The best fit lines of the reaction tests for the various sounds.

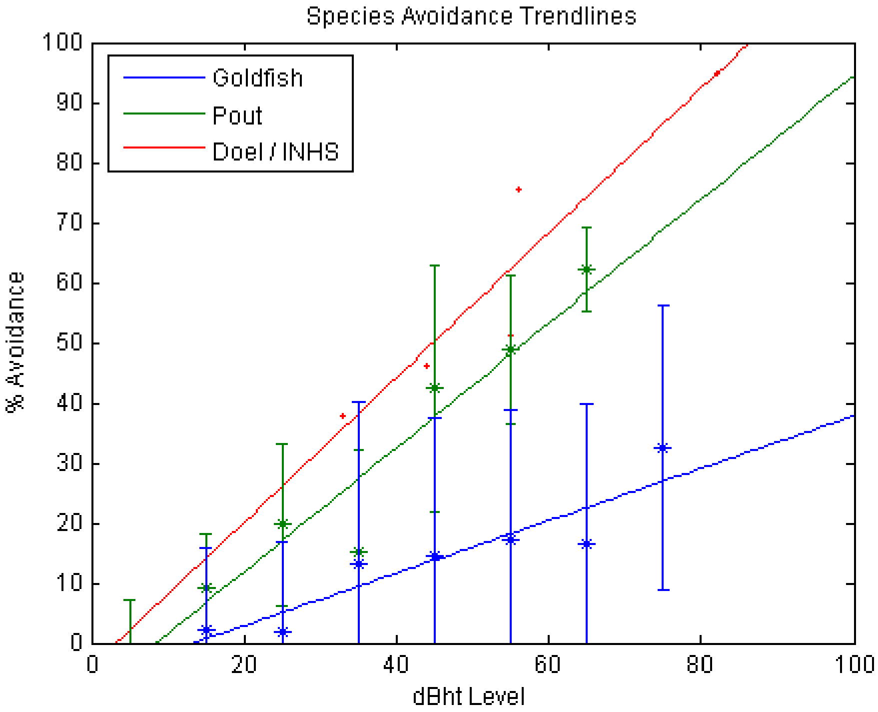

Figure 41. Synthesis of the experimental data. Comparison of results for the reaction tests and the Doel / INHS data.

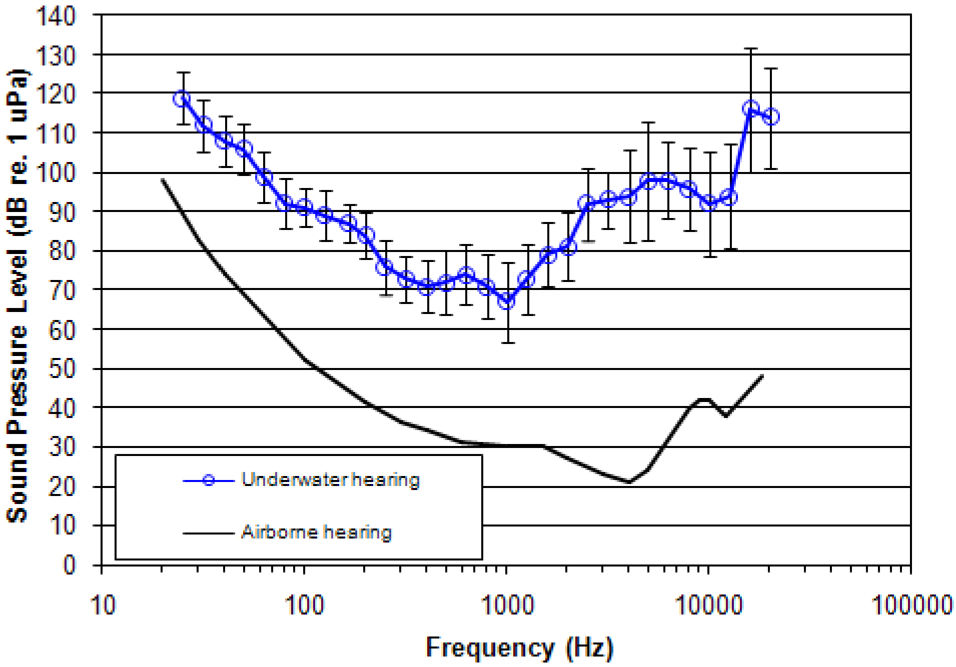

Figure 42. Comparison of human Minimum Audible Field (MAF) airborne and underwater hearing threshold (Parvin et al, 1995, Parvin, 1998).

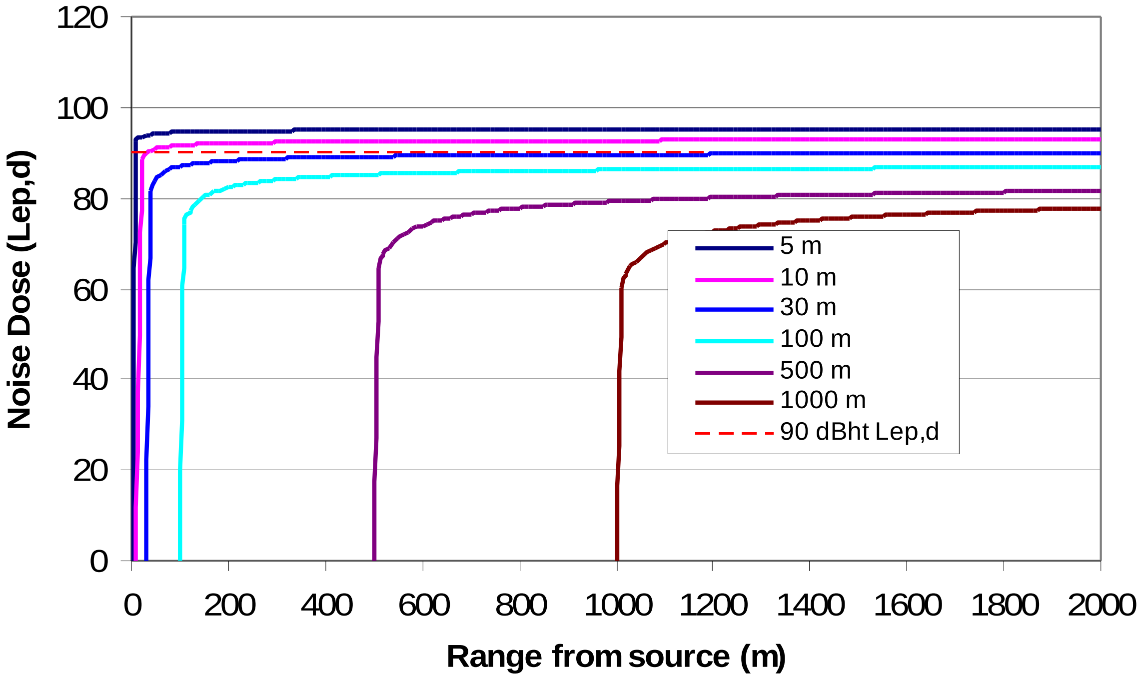

Figure 43. Herring cumulative Noise Dose with range from a 6.5 m diameter impact piling operation. Data are presented for animals at ranges from 5 m to 1000 m at the start of piling (swim speed 1 m.s^{-1}).

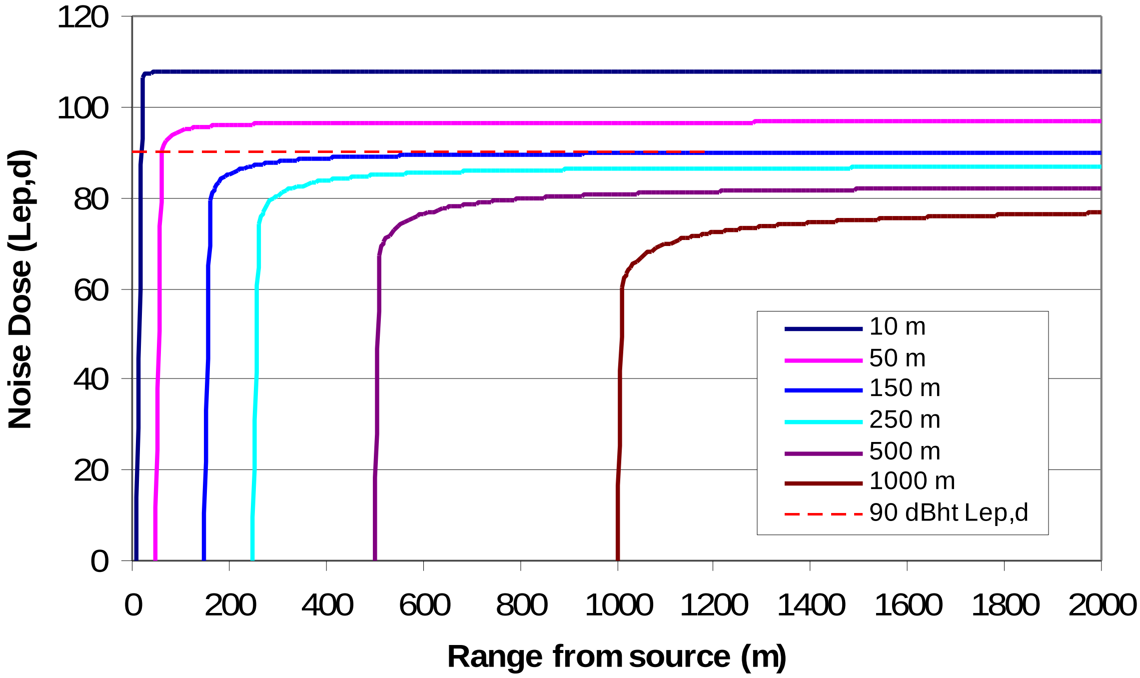

Figure 44. Harbour porpoise cumulative Noise Dose with range from a 6.5 m diameter impact piling operation. Data are presented for animals at ranges from 10 m to 1000 m at the start of piling (swim speed 1 m.s^{-1}).

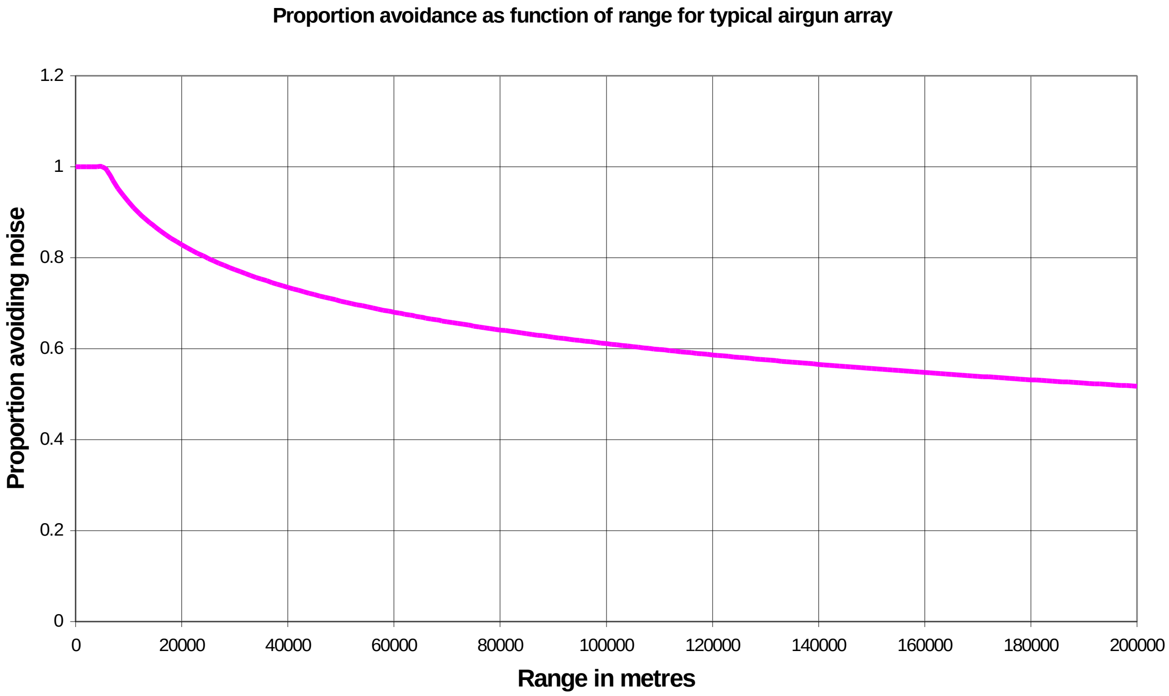

Figure 45.The proportion of a species predicted to avoid an airgun array, versus range.

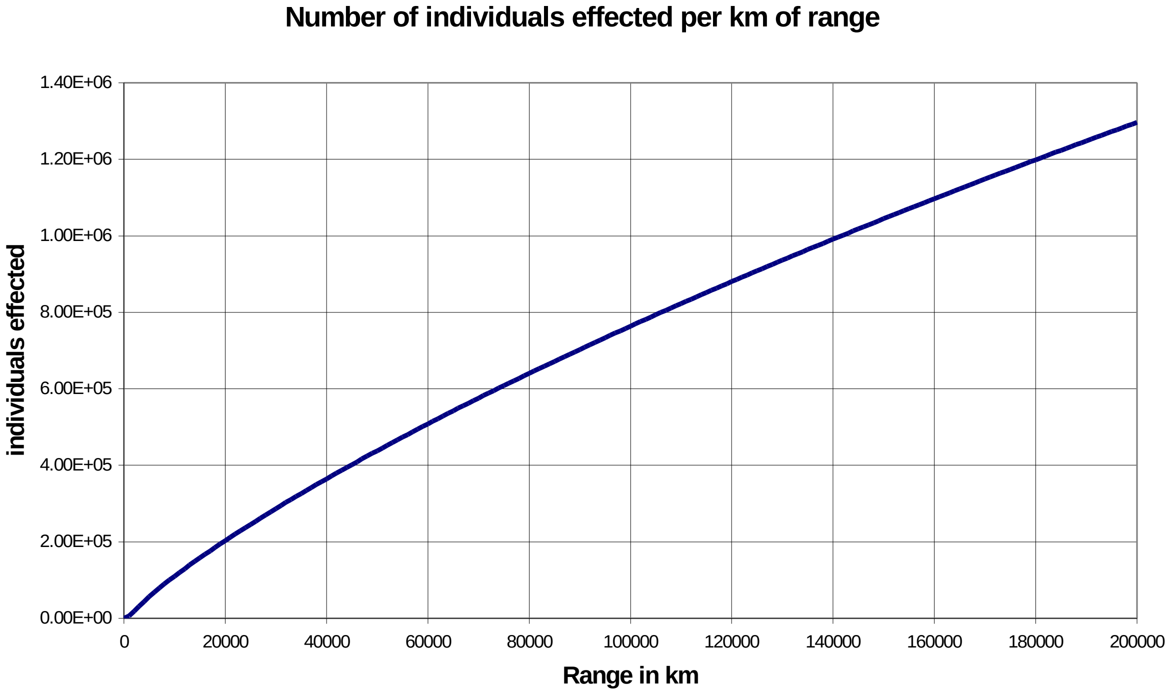

Figure 46. The number of individuals affected by the array per km of range from the airgun, as a function of range.

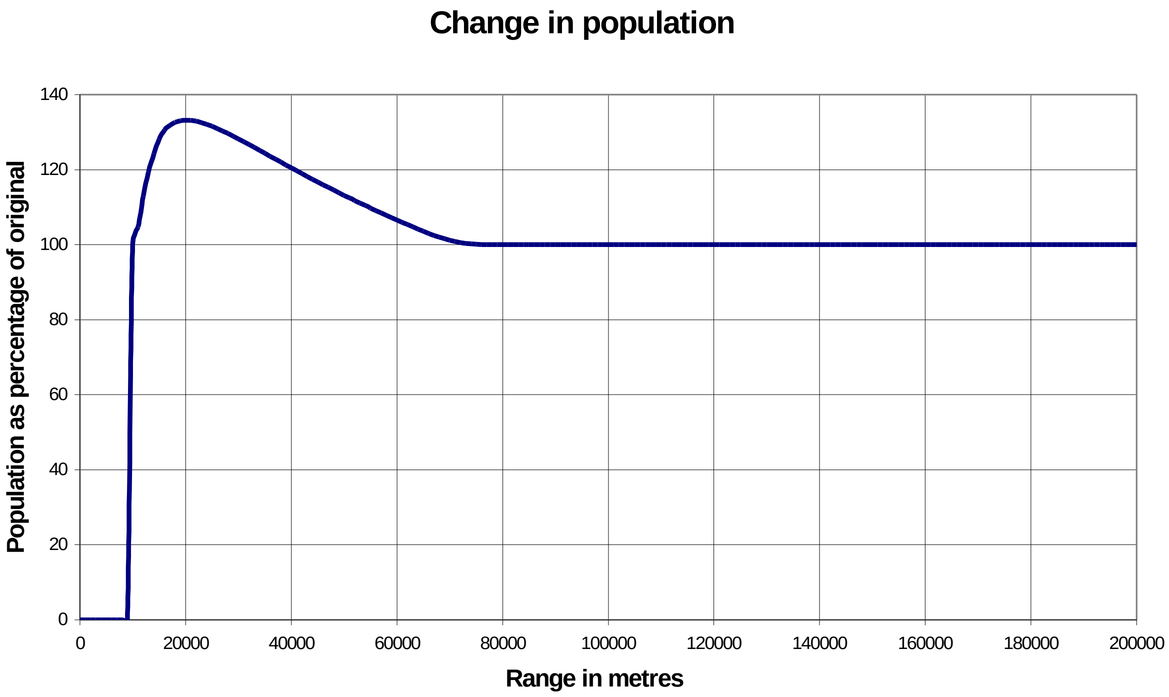

Figure 47. An estimation of the population distribution of cod around a seismic survey based on the dB$_{ht}$ model.

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Issue	Date	Details of change
534R1201	15/6/06	First draft, by JRN.
534R1220	20/2/07	Final draft for review & comment.
534R1221	26/3/07	Amendment following review.
534R1231	24/10/07	First issue.

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