REVIEW

Hearing in fish and their reactions to sounds from offshore wind farms

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ABSTRACT: The current knowledge on detection of, and reaction to, sound by fish is reviewed, with special emphasis on underwater noise from offshore wind farms. The detection distance to wind farms for 3 species of fish representing various hearing capabilities varies between 0.4 and 25 km at wind speeds of 8 to 13 m s^{-1}. The detection distance depends on the size and number of windmills, the hearing abilities of the fish, background noise level, wind speed, water depth and type of sea bottom. The noise from windmills may decrease the effective range for sound communication of fish; however, it is not known to what extent this decrease affects the behaviour and fitness of fish. Windmill noise does not have any destructive effects upon the hearing abilities of fish, even within distances of a few metres. It is estimated that fish are consistently scared away from windmills only at ranges shorter than about 4 m, and only at high wind speeds (higher than 13 m s^{-1}). Thus, the acoustic impact of windmills on fish is restricted to masking communication and orientation signals rather than causing physiological damage or consistent avoidance reactions. These conclusions must be viewed with great caution, however, as the existing data are prone to large uncertainties. Further studies on more detailed measurements of the sound-field and of fish behaviour around windmills are needed.

KEY WORDS: Bioacoustics · Detection range · Fish communication · Hearing in fish · Sea-based wind farm

INTRODUCTION

Several industrial countries are planning to construct large sea-based wind farms along their coasts. The environmental impact expected from such developments has not yet been completely evaluated. One major issue is whether or not the underwater sounds emanating from the windmills would affect fish and marine mammals (Hoffmann et al. 2000). Recently, it has been shown that marine mammals may react to sounds from windmills within a range of a few hundred metres (Koschinski et al. 2003); however, it is not known to what extent this reaction poses a serious problem for the animals. We also lack knowledge with which to assess to what extent the animals become habituated to the sounds after long-term exposure.

To our knowledge, there are only a few reviews and reported measurements of the reactions of fish to windmill sound. Westerberg (1994) measured both windmill noise and the reaction of fish to it, but his study was limited to a single windmill of relatively small size. Hoffmann et al. (2000) concluded in their review that fish are not affected by windmill noise except for mechanical disturbance during the construction phase. Vella et al. (2001) and Smith & Westerberg (2003) focused their reviews on our previously very limited knowledge on both underwater sounds from windmills and on how fish perceive and react to

underwater noise, and did not take into consideration new and more detailed measurements of sounds from offshore windmills by Degn (2000), Fristedt et al. (2001) and Ingemansson (2003). In addition, recent studies have shown that continuous exposure to sound of high intensity can cause inner ear damage to fish (Hastings et al. 1996, McCauley et al. 2003). It seems important to re-evaluate the possible impact of windmill noise on fish in the light of these new studies.

The present review begins with an outline of some important principles of underwater acoustics, with special emphasis on hearing in fish and their reaction to sound. Subsequently, the possible effects of windmill sounds on fish are evaluated in terms of detection distances, communication masking and damage to hearing.

SOUND AND FISH

Underwater sound: decibels

Some issues of acoustics relevant to our discussion are not readily available in the acoustic literature. The important concepts of near and far fields are particularly confusing. Bioacousticians use these terms to describe either acoustic interference or range-dependent variations in acoustic impedance. Below we clarify the difference between these fields, as well as other technical issues important when discussing sound from windmills. Most of what is treated here has been synthesised from a variety of textbooks and reviews, especially those by Beranek (1983), Urick (1983), Kalmijn (1988, 1989), Rogers & Cox (1988), Medwin & Clay (1998) and NRC (2003).

An acoustic wave is generated by longitudinal particle displacement of the carrier medium (e.g. air, water). Such displacement creates local pressure oscillations that travel with a sound velocity (c), determined by the compressibility and density of the medium. The intensity of the acoustic field is defined as the vector product of the local pressure fluctuations (p) and the velocity of the particle displacement (v). The pressure fluctuation and particle displacement are related by the equation $p = vZ$, where Z is the acoustic impedance of the medium. This formula is called Ohm's law of acoustics, because of its similarity to the equation in electronics. In the free acoustic field (with no reflecting boundaries, and a homogenous sound velocity) and at a distance of several wavelengths from the sound source, acoustic impedance is $Z = \rho c$, where ρ is the density of the medium.

Acoustic intensity (I) can be calculated by measurements with a pressure transducer using $I = pv = p^2/Z$. In the free acoustic field, this equation can be expressed as $I = p^2/(\rho c)$, so that acoustic intensity can be

calculated from pressure measurements. Usually the intensity of sound is measured in decibels (dB), calculated as $20 \log_{10}(p/p_0)$, where the reference pressure p_0 is chosen as 1 µPa in underwater acoustics.

In the free acoustic field, the particle velocity component may be calculated from pressure measurements using the formula $v = p/(\rho c)$. Close to a sound source, or in shallow water, acoustic impedance deviates considerably from the free-field expression ($Z = \rho c$), and consequently the relationship between pressure fluctuations and particle velocity is more complicated (Fig. 1a). 'Close' and 'shallow' are here defined relative to the wavelength of the signal, which in the case of sounds relevant to hearing in fish ranges from ~1 to >1 km. The fact that particle velocity (as opposed to sound speed, c) may be much larger close to a sound source is important in the context of hearing in fish, as will become obvious from the following discussion.
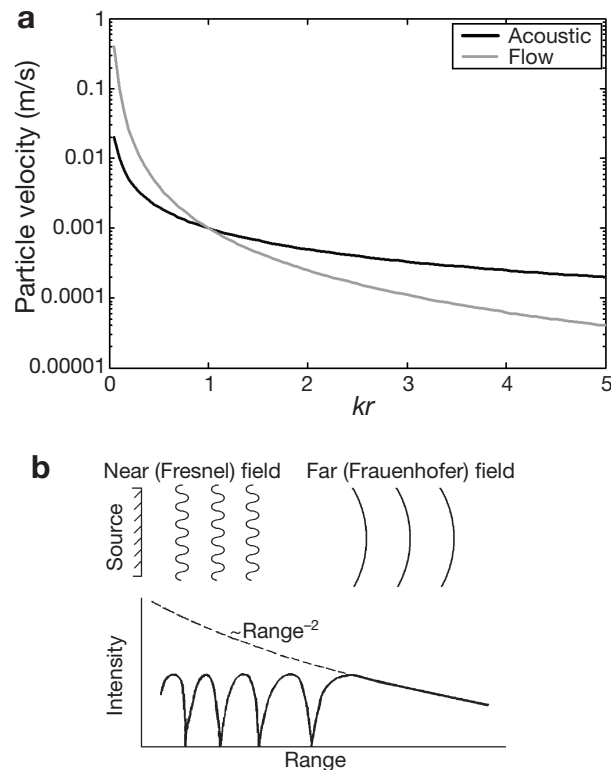

Fig. 1. Two types of near- and far-field regions around an acoustic source. (a) Near-field flow from a monopole (pulsating) sound source: at ranges within $kr = 1$ (where k is emitted wave number, $k = 2\pi/\lambda$, and r is range to the sound source), contribution of local flow to particle velocity ('Flow') is larger than contribution of the travelling wave ('Acoustic'). (b) Fresnel near-field: close to a sound source, at ranges within about $r_0 < ka^2$, where a is radius of the sound source, sounds produced by various parts of the source interfere and thereby create complicated range-dependent intensity variations. Outside the near-field, in the Frauenhofer far-field, sound intensity decreases smoothly (as r^{-2}) due to spherical spreading. Adapted from Urick (1983), with permission from Peninsula Publishing, USA

It is much more difficult to measure the particle velocity component of the acoustic field than the acoustic pressure component. In the acoustic free field the 2 components are interrelated with the proportion-ality factor $Z = \rho c$. Therefore the magnitude of the free acoustic field is entirely described by measurements with 1 hydrophone. Close to a sound source, in the so-called 'acoustic flow near-field', 1 hydrophone does not suffice to describe the magnitude of the velocity component and either a second hydrophone or an accelerometer is needed.

Further complications of acoustic propagation occur due to interference (Fig. 1b). Close to a sound source, sounds produced by various parts of the source inter-fere, creating a complicated spatial pattern of peaks and troughs in acoustic intensity. The extent of this area, called the 'Fresnel zone' or the 'acoustic interfer-ence near-field', is a function of the ratio between the cross-section of the sound source to the emitted wave-length. Another way to describe this is to say that beyond the Fresnel zone the source may be regarded as a point-source, whereas within the Fresnel zone it cannot. The range of the Fresnel zone is very limited for windmills at the wavelengths of interest for hearing in fish, ranging from a few tens of metres to ≪1 m. For frequencies that scare away fish (with wavelengths >100 m), the range of the Fresnel zone around a windmill is <1 m.

In shallow water, interference also occurs due to reflexions at the sea surface (Lloyd mirror effect) and at the sea floor. In windmill parks, additional complex-ity of the sound field may occur due to interference of sound from different windmills. The interference pat-terns generated from the sea surface, sea floor and adjacent windmills may extend over distances from the wind farm that are greater than inter-windmill distances and water depth.

During propagation through the medium, the inten-sity of the acoustic waves is reduced due to 'geometric spreading', 'absorption', 'refraction' and 'reflection'. Geometric spreading is caused by 'dilution' of acoustic energy over a larger and larger area as it spreads out from the source. Absorption is due to a complicated mixture of pressure-dependent molecular coupling in the water. It has very little effect at frequencies and ranges of interest here. Refraction is the effect of sound rays being bent as they pass through a medium of inhomogeneous sound velocity, analogous to light rays being bent when passing through a lens. Reflection causes positive or negative interference between sound paths being reflected at, for example, the water surface, the bottom or from a submerged object.

The reduction of sound intensity is expressed by the transmission loss $TL(r)$, defined as $TL(r) = SL - RL(r)$. Here, SL is the source level of the sound (the sound intensity by convention back-calculated to a range of 1 m from the sound source on the acoustic axis if any[1]) and $RL(r)$ is the received level (the sound intensity at a range r metres from the sound source). SL, $RL(r)$ and $TL(r)$ are measured in decibels. Absorption is <0.1 dB km^{-1} at the low frequencies considered here (<1 kHz) and can therefore be neglected at ranges up to many tens of kilometres. In the free acoustic field, geometric spreading is given by 20 log r, i.e. so-called spherical spreading. In shallow water, the geometric spreading approaches cylindrical spreading and can be approxi-mated as 10 log r.

An additional complication to shallow-water propa-gation is that wavelengths larger than about 4 times the water depth cannot propagate as acoustic waves. The exact cut-off wavelength depends on the sound velocity of the bottom material. For example, at a water depth of 20 m, sound propagation is precluded for wavelengths greater than about 80 m, or frequencies below 18 Hz, if the bottom is made from a material with a very high sound velocity. Sound energy may still appear in terms of local pressure and particle-displacement fluctuations, but propagation of acoustic waves is not possible.

Hearing abilities of fish

The description of hearing in fish below is based on comprehensive papers by Chapman & Hawkins (1973), Sand (1974), Schuijf (1983), Fay (1984), Kalmijn (1988, 1989), Popper & Fay (1993), Edds-Walton & Fay (1998), Lu & Popper (1998), and Popper et al. (2003). This sub-section is focussed on issues related to our discussion on windmill noise.

The inner ear of fish is primarily sensitive to particle displacement in the acoustic field, or rather its time-derivatives particle velocity and acceleration. Thus, the fish ear should primarily be viewed as an accelero-meter rather than a pressure detector. Fish that possess a swim bladder, such as cod *Gadus morhua* and her-ring *Clupea harengus*, can detect the pressure oscil-lations of the acoustic field in addition to particle acceleration.

Fig. 2 shows the hearing abilities of a few selected species of fish. In the low-frequency range (Fig. 2a, measured in units of acceleration), all fish species seem to have similar hearing ability. At higher frequencies (Fig. 2b, measured in units of sound pressure) the hear-

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[1]The source level is here used to predict the sound level in the acoustic far field; if the range of the flow or Fresnel near-fields is >1 m, the actual sound intensity at 1 m distance from the sound source may be considerably different to that predicted by the source level
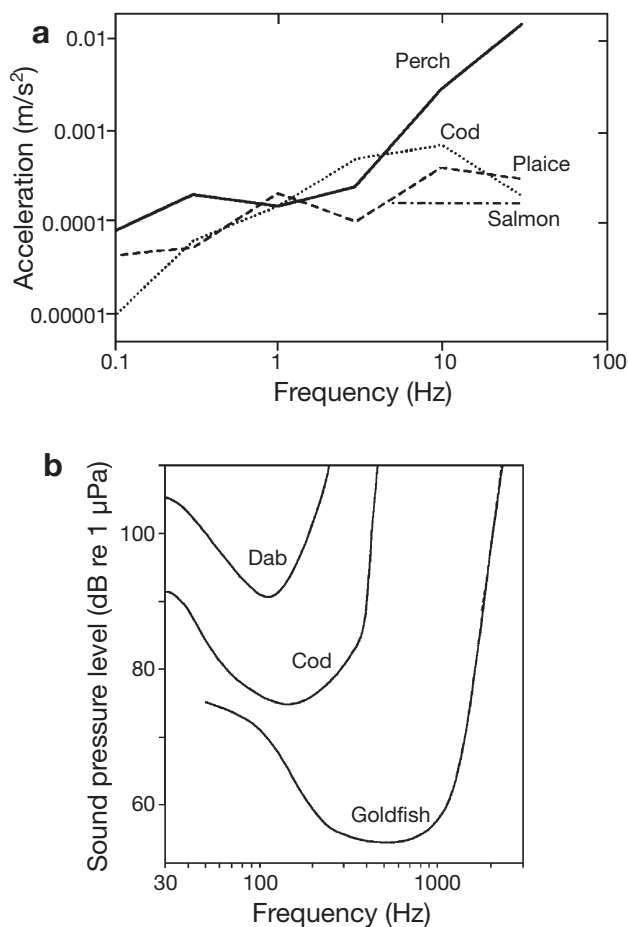
Fig. 2. Hearing abilities of selected fish species at (a) infrasonic and (b) sonic frequencies. Data (sources) are: dab *Limanda limanda* (Chapman & Sand 1974), cod *Gadus morhua* (Sand & Enger 1973, Sand & Karlsen 1986), goldfish *Carassius auratus* (Fay 1969), plaice *Pleuronectes platessa* (Karlsen 1991b), perch *Perca fluviatilis* (Karlsen 1991a) and Atlantic salmon *Salmo salar* (Hawkins & Johnstone 1978)

ing ability varies dramatically, depending on the presence of a swim bladder, its air content, and if a connection between the swim bladder and the inner ear exists. Flatfish, such as the dab *Limanda limanda*, have no swim bladder and are therefore relatively insensitive to sound (Fig. 2b). We therefore denote such species 'non-specialists'. The swim bladder of Atlantic salmon *Salmo salar* may normally contain a little amount of air, and the hearing sensitivity of this species is therefore similar to that of dab (Hawkins & Johnstone 1978). Cod *Gadus morhua* has more air in its swim bladder and is therefore more sensitive to sound and denoted a 'hearing generalist'. Catfish and carp (such as the goldfish *Carassius auratus*) have anatomical structures facilitating the transfer of sound energy from the swim bladder to the inner ear, making these species much more sensitive to sound; they are therefore denoted 'hearing specialists' (Fig. 2b). Early data

by Enger (1967) suggested that clupeids (such as the Atlantic herring *Clupea harengus*) have a hearing sensitivity similar to other hearing specialists, but recent data by Mann et al. (2001) suggest that this group is less sensitive to sound than the non-specialists, albeit the bandwidth of their best-hearing threshold is wider than that of the specialists. Fishes are mainly sensitive to sound of frequencies below 0.5 to 1 kHz, and they can hear lower frequencies than humans (so-called 'infrasound'). The underwater sound intensity at the lowest hearing threshold of goldfish *Carassius auratus* roughly corresponds to the in-air sound intensity at the lowest hearing threshold for most land vertebrates (including humans)[2].

The inner ear-organ of fish is probably sensitive to the direction of the sound source, even though it is not yet completely clear how this is accomplished. In addition, Schuijf & Hawkins (1983) showed that cod are able to estimate the distance to the sound source within the acoustic near-field. This may be achieved by comparing the magnitude of the sound pressure and particle velocity components, but more data is needed to confirm this.

Besides this classical description of hearing in fish, there are 2 other important issues that need to be evaluated. First, it has recently been discovered that shad (*Alosa sappidissima*, a herring-like fish) show consistent evasive reactions to ultrasound of intensities above about 185 dB re 1 µPa (Mann et al. 2001, Plachta & Popper 2003). However, windmills do not produce ultrasound (Degn 2000), so these new findings are not relevant for our present review.

The other issue is the lateral line system, consisting of arrays of neuromasts mainly located in canals on the fish body. The major purpose of the lateral line system is not to detect acoustic waves, but to detect local low-frequency (below 150 Hz) water flow relative the fish body (Sand 1984, Enger et al. 1989). Nevertheless, the lateral line can detect the acoustic field very close to a

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[2]The sensitivity of the vertebrate ear responds to the energy content of the signal which, for continuous signals, is proportional to the intensity of the acoustic signal. As the acoustic impedances of air and water are very different, 2 acoustic signals with equal sound-pressure levels above and under water do not have the same acoustic intensity. Furthermore, sound intensities in air are usually reported with a different reference unit (20 µPa) to those under water (1 µPa). The goldfish best-hearing threshold is at a sound intensity of about 50 dB re 1 µPa under water, which corresponds to an intensity of –12 dB re 20 µPa in air. This is obtained by subtracting 26 dB from the 50 dB to account for the difference in reference units (20 $\log_{10}$ [20/1] = 26 dB), and subtracting another 36 dB to account for the difference in acoustic impedance between air and water: 10 $\log_{10}$ ($p_{water}c_{water}$ / $p_{air}c_{air}$) = 10 $\log_{10}$ (1.5×10^6/340) = 36 dB. Humans hear best at a frequency of about 3.5 kHz, where the threshold is about –10 dB re 20 µPa (Beranek 1993)

sound source (well within the acoustic flow near-field). Its limited detection range probably makes the lateral line system unimportant in the context of the reaction of fish to acoustic signals from windmills.

Fish sound-detection

A large part of the literature on fish sound-detection and processing deals with the problem of detecting signals in noise (Fay & Megala Simmons 1999). The signal is merely defined as the sound stimuli of interest for the subject, whereas the noise is either external (ambient) or internal (determining the hearing threshold) in the hearing system, or both. For all biological hearing systems studied to date, it seems that the perceived noise level is integrated within a frequency band called the critical band (Fay 1991). The bandwidth of this filter is frequency-dependent. The filters may not be static, but can vary depending on the detection task (e.g. the bandwidth of the signal; see Swets 1964 for discussion). This makes the interpretation of the critical band concept difficult. Still, studies have shown that integrating the noise over a certain bandwidth in signal detection tasks is useful for modelling the signal-detection abilities of most, if not all, vertebrates (Fay 1991).

There have been very few studies determining the nature of the critical bands in fish. Therefore, the results arising from our calculations are greatly prone to inaccuracies arising from insufficient data. Hawkins & Chapman (1975) estimated the filtering bandwidth of cod *Gadus morhua* at 160 Hz to be 72 Hz. Hawkins & Johnstone (1978) made similar measurements on Atlantic salmon *Salmo salar* and showed that the filtering bandwidth at the same frequency was 183 Hz. For the goldfish, a hearing specialist, the filtering bandwidth at 160 Hz is 50 Hz (Fay 1974). The bandwidth increases with higher centre frequency, so that Q (the bandwidth divided by the centre frequency) is approximately constant (Fay 1991). These results are consistent with those of a recent study on sciaenids, which revealed that the effects of masking varies with the hearing capabilities of the fish (Ramcharitar & Popper 2004).

The received noise level can be determined by transforming the bandwidth (BW) of the filter into decibels. This is added to the spectral noise level (N_0, in dB re 1 µPa $Hz^{-1/2}$) to obtain the received noise level (NL, in dB re 1 µPa):

$$NL = N_0 + 10 \log_{10} BW \qquad (1)$$

This assumes that the noise spectral density is constant over the critical band, and that the bandwidth of the noise is at least as wide as the filtering bandwidth.

It is important to note that this technique differs from that used to process narrow-band signals, i.e. signals with a bandwidth narrower than the critical band. If the signal contains both narrow- and broad-band components, these components may be treated independently (i.e. the filtering band width added to the broad band but not to the tonal components, as these have a very narrow bandwidth), and the levels may then be summed to obtain the total perceived sound level: total = tonal + broadband, where both the tonal and broadband intensities are measured in units of the RMS (root-mean-square) intensity:

$$p_{RMS} = \sqrt{\frac{1}{T} \int_T p(t)^2 \mathrm{d}t} \qquad (2)$$

where the time (T) chosen is long enough to cover the whole signal or an appropriate interval of the signal. The integration variable t is the time scale of the pressure fluctuations (usually measured in s). We follow this procedure for the calculations of the windmill sounds, as these sounds contain both tonal and broadband components.

A large part of the following deals with the problem of determining how far away a sound source may be detected in ambient noise. This problem can be pursued with different forms of the passive sonar equation, either

$$DT = RL(r) - (NL - DI) = SL - TL(r) - (NL - DI) \qquad (3)$$

(Urick 1983), or

$$DT = RL(r) - HT = SL - TL(r) - HT \qquad (4)$$

where DT is the detection threshold (the difference between signal and noise at threshold), $RL(r)$ is the received sound level, NL is the received noise level, DI is the receiver directionality index (the reduction in received ambient noise due to directional hearing), SL is the source level, $TL(r)$ is the transmission loss, and HT is the hearing threshold (all measured in decibels). Eq. (3) is used if $NL - DI > HT$ (detection limited by ambient noise), and Eq. (4) if $NL - DI < HT$ (detection limited by the hearing threshold).

The task is now to solve for the range, r, between the source and the receiver at threshold. The remaining parameters in Eqs. (3) & (4) need to be known. In the case of fish and windmills, we have only vague conceptions for some of the parameters. There are few data on how fish perceive signals in noise. Likewise, we have very little knowledge of which detection threshold is needed for a fish to decide that a signal is present in noise. In addition, we do not really know how the directional hearing properties of fish reduce the perceived ambient noise level (i.e. DI has to our knowledge not been assessed for fish). Finally, very few measurements exist on underwater sound fields around windmills. Therefore, our maximum detection-range calculations must be viewed with great caution.

Fish reaction to sound

All fishermen know that fish react to sound, either being attracted or scared away from the sound source. This knowledge has been exploited by traditional fishing techniques, and scientific investigations on the topic have been performed since the 19th century (Popper & Carlson 1998, Wahlberg 1999). Still, knowledge on how fish make use of acoustic information and how they react to it is rather poor. Acoustic communication is frequently used in courtship and aggression by many fish species (Hawkins & Rasmussen 1978, Hawkins 1993, A. V. Soldal & B. Totland pers. comm.), but there are very few measurements on the acoustic properties of such sounds. In addition to communication, passive listening may be used to detect predators and prey, and for orientation purposes (Popper & Fay 1993, Fay & Popper 2000, Popper et al. 2003), and some

fish may even use sound as a primitive form of echo location (Tavolga 1971).

Although some research has focused on how fish react to anthropogenic sound, little is known about this issue (Popper 2003). Previously, most studies were made on commercially important fish species such as Atlantic salmon *Salmo salar*, eels *Anguilla anguilla* and cod *Gadus morhua*. Today interest has shifted towards species commonly held in laboratories, such as goldfish *Carassius auratus*. There is a complete lack of knowledge about most fish species. The initial studies of anthropogenic noise were made to study the effects of ship noise (Mohr 1964, Olsen 1971) (Fig. 3a). Subsequently, studies were made on other sound sources, such as acoustic scaring devices at hydroelectric plants (reviewed by Carlson & Popper 1997 and Popper & Carlson 1998) and seismic air guns (Booman et al. 1996, Engås et al. 1996) (Fig. 3b). These investigations showed that fish respond to sound in highly variable ways, depending on the nature of the sound, the species investigated, and the experimental methodology. Many different kinds of sound may evoke a reaction, even at modest sound levels: swimming reactions were noted at a received-sound level of ~120 to 130 dB re 1 μPa when vessel noise was played back to herring and cod (Engås et al. 1995), and also at comparatively low sound levels when wind-generated noise was played back to sole *Solea solea* (Lagardère et al. 1994). However, in many studies it is not known if fish become habituated when exposed to modest sound levels for prolonged time periods.

Fishes may only consistently be scared away from a sound source of very low frequencies and very high levels of particle acceleration. One of the most well studied species is juvenile Atlantic salmon *Salmo salar*; for this species the frequency of the stimuli should be below 20 Hz (Knudsen et al. 1992, Sand et al. 2001). The acceleration threshold for consistent deterrence is ~10^{-2} ms^{-2}, corresponding to an acoustic intensity of ~160 dB re 1 μPa in the acoustic free field (Sand et al. 2001). There is still some discussion as to whether this avoidance reaction is mediated by the inner ear or lateral line (A. N. Popper pers. comm.). Also, it is not known whether these results can be generalised to other fish species. Many more studies are needed to understand how various fish species
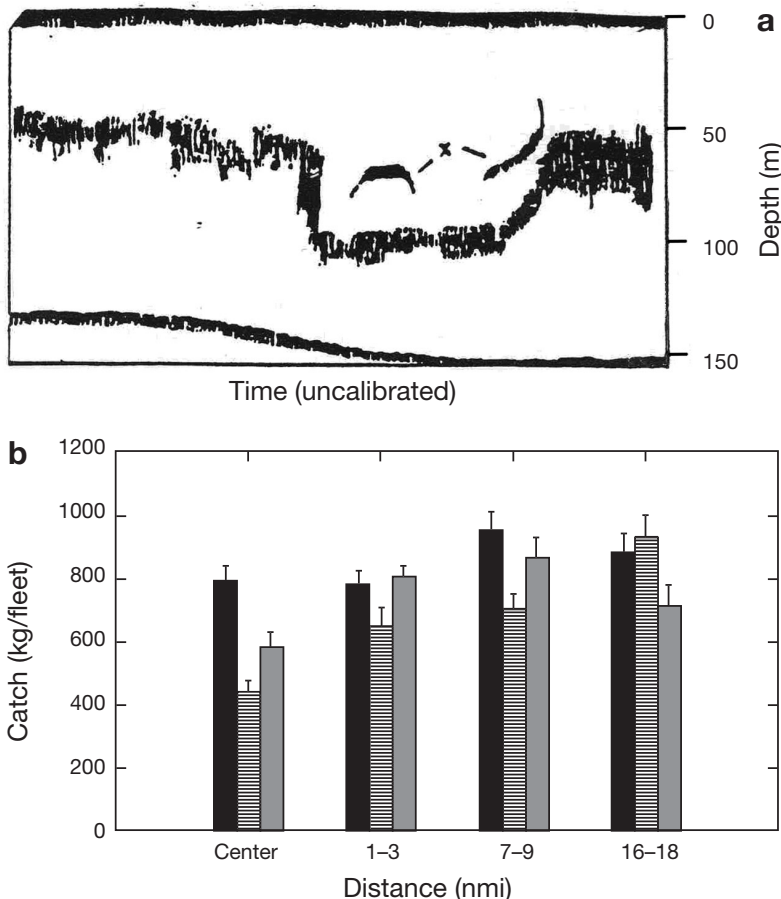

Fig. 3. Results from 2 studies assessing effect of sound on fish. (a) Echo sounder track of herring school diving when approached by a trawl (×) from a fishing vessel. (Mohr 1964). (b) Average longline catch rates (mean + SE, N = 4 to 7 longlines) of cod before (black), during (striped) and after (grey) a seismic survey using an air gun array (peak source level 253 dB re 1 μPa at 1 m, frequency emphasis 10 to 150 Hz, used continuously during 114 h in a 3 × 10 nmi area) as a function of distance from the shooting area (1 nmi = 1852 m). From Engås et al. (1996), with permission of NRC Research Press, Canada

react to both stationary and mobile anthropogenic noise sources.

The only study known to us on how fish react to windmill sounds was made with ultrasonic telemetry and fishing trials by Westerberg (1994), who showed that silver eels *Anguilla anguilla* did not change their swimming behaviour significantly when passing at a distance of 0.5 km from a small (200 kW single-unit) offshore windmill. However, the catchability of cod *Gadus morhua* and roach *Rutilus rutilus* increased by a factor of 2 within 100 m the windmill when the rotor was stopped under otherwise similar conditions.
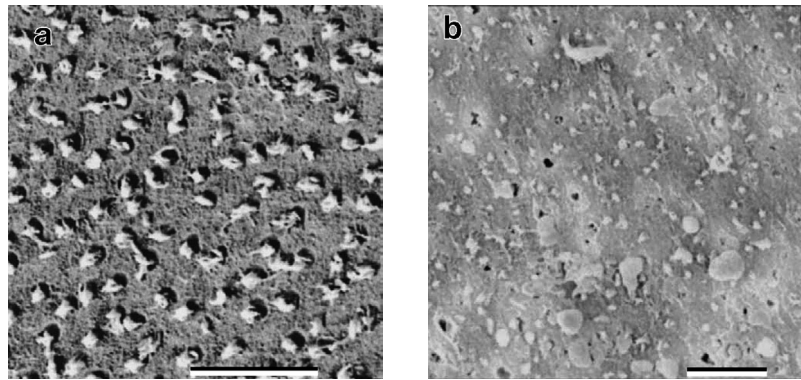

Fig. 4. *Pagrus auratus.* Sensory epithelia in the inner ear of a pink snapper (a) before and (b) after exposure to sounds from an airgun. Scale bars = 20 μm. From McCauley et al. (2003), with permission of the Acoustical Society of America

Sound-induced hearing loss

High-intensity sound can cause temporary or permanent hearing loss. There is little data quantifying such effects on fish. Early accounts, include that by Enger (1981), showing that the inner ear of fish can be damaged by intense sound. Hastings et al. (1996) observed damage to the inner ear of oscars *Astronotus ocellatus* exposed to a 300 Hz continuous tone at 180 dB re 1 μPa; damage was not observed at lower intensities at a frequency of 60 Hz. McCauley et al. (2003) exposed fish (pink snapper *Pagrus auratus*) to airgun pulses at a maximum received sound level of 180 dB re 1 μPa, the signal energy being mainly in the frequency range of fish hearing. This induced damages to the sensory epithelia of the fish ear, with no obvious recovery 58 d after exposure (Fig. 4). In another experiment by Smith et al. (2004), goldfish *Carassius auratus* and tilapia *Oreochromis œniloticus* were exposed to white noise (bandwidth 0.1 to 4 kHz, received sound level 164 to 170 dB re 1 μPa) for 28 d. There was a large difference in the effect of the noise on the hearing abilities of the 2 species. Goldfish with their very acute hearing abilities experienced a temporary threshold shift of 25 dB within as little as 7 d after noise exposure. In contrast, the only effect observed on the tilapia (which have much poorer hearing abilities) was a 10 dB shift in the hearing threshold at a single frequency (800 Hz) after 28 d exposure to noise. In a study by Scholik & Yan (2001), fatheaded minnows *Pimephales promelas* (a hearing specialist) exposed to white noise (0.3 to 4 kHz, 142 dB re 1 μPa for 24 h) showed significant hearing loss. It is not yet known whether it was the pressure or the velocity component of the acoustic field that induce the ear damage reported in these studies.

Gaps in our knowledge of fish reaction to sound

It should be emphasised that the reaction of fish to sound has only been studied in a limited number of species, and the existing data cover only a few signal types and sound levels. Great care is needed when extrapolating existing data to other species and sound types and in different environmental and behavioural contexts. We know very little about how fish react to sound stimuli, and how much damage is induced to fish by anthropogenic noise. Although more than 100 yr have passed since the advent of the first engine-powered boats, we still know little about the effects of vessel noise on fish. Possible effects from stress arising from prolonged exposure to levels of lower noise levels that do not induce physiological damage have not yet been well investigated. Also, recovery abilities after hearing loss need to be more thoroughly documented.

Finally, we know very little about how fish eggs, larvae and juveniles may be affected by sound as compared to adult fish (Banner & Hyatt 1973, Dalen & Knutsen 1987, Knudsen et al. 1992, Booman et al. 1996, Kenyon 1996, Leis et al. 2002, Tolimieri et al. 2004). Dalen & Knutsen (1987) observed no significant change in survival of cod *Gadus morhua* eggs after exposure to close-range airgun pulses. There seems to be an increase in the alarm susceptibility to acoustic stimuli during the larval stages in the red drum fish *Scianeops ocellatus* (Fuiman et al. 1999) and an increase in pressure sensitivity in larval stages of the herring *Clupea harengus* (Blaxter & Denton 1976). During further growth, the very limited evidence available suggests that hearing sensitivity does not change significantly in zebrafish *Danio rerio* (Higgs et al. 2003). From this very rudimentary data one may hypothesise that juvenile fish are at least as sensitive to sound disturbances as adults, whereas larvae and eggs may be less sensi-

tive; however, before any conclusions can be drawn, more studies on this are needed.

PREDICTING FISH REACTIONS TO WINDMILL SOUNDS

Sounds from offshore windmills could have a wide range of effects on fish. Here we discuss 3 factors that we consider could be of major importance for their survival and fitness: (1) masking of acoustic communication; (2) consistent triggering of alarm reactions; (3) temporal or permanent hearing damage. There may be other important factors not covered here, such as stress due to long-term exposure to high sound levels. We begin by trying to estimate within which ranges fish may be able to detect the sounds from offshore wind farms.

Noise from windmills

Underwater sound from offshore windmills has to our knowledge only been investigated in 4 studies: Westerberg (1994), Degn (2000), Fristedt et al. (2001), Ingemansson (2003). The properties of the windmills investigated in these studies are listed in Table 1 and Fig. 5a sums up the measurements, back-calculated to a distance of 1 m (assuming cylindrical spreading). The acoustic measurements for windmills by Ingemansson (2003) comprised substantially higher sound levels than did the other studies (Fig. 5a). The difference may be attributable to size, different kinds of windmill fundaments, source directionality or other construction/environmental features
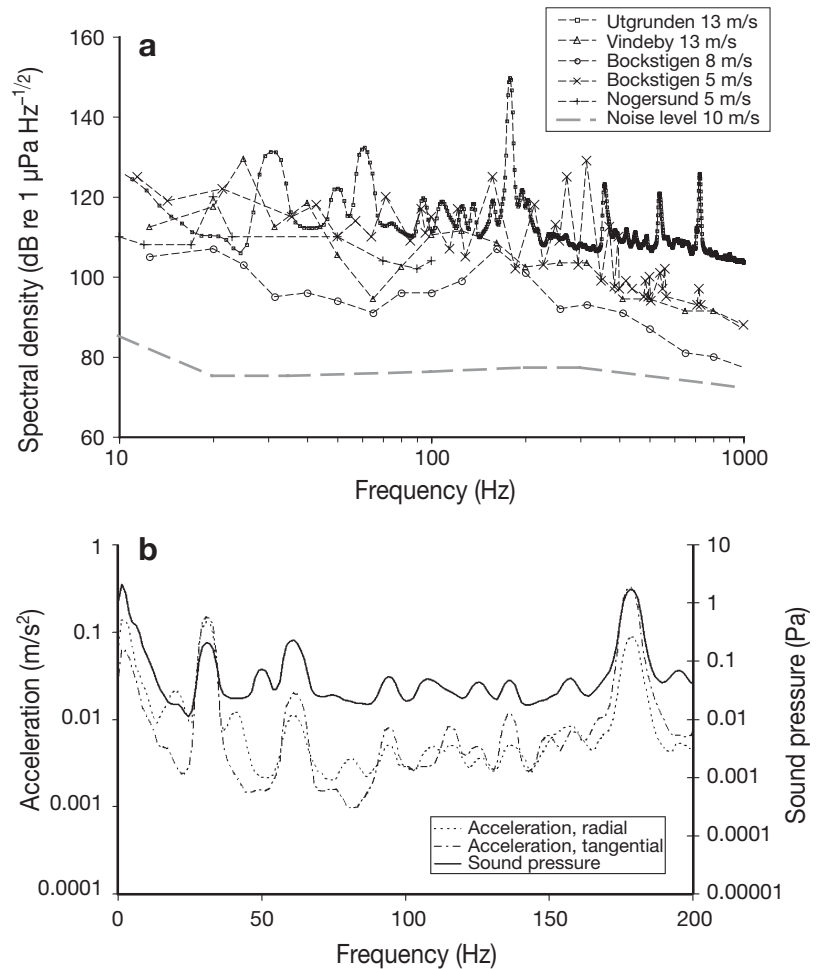
Fig. 5. (a) Source-level measurements of windmill sounds by Westerberg (1994: Nogersund), Degn (2000: Bockstigen 8 m s^{-1} and Vindeby), Fristedt et al. (2001: Bockstigen 5 m s^{-1}) and Ingemansson (2003: Utgrunden). Noise level: background noise level measured by Piggott (1964) in 40 to 50 m water depth. See Table 1 for properties of windmills recorded. (b) Radial and tangential acceleration of the turbine tower compared to sound-pressure measurements made at Utgrunden windmill park, Sweden (Ingemansson 2003). 50 Hz peaks in pressure spectra in both (a) and (b) were caused by electric noise

(Table 1). Windmill type has a large effect on the sound intensities generated, and therefore also on the range at which fish may be affected. Additional factors, especially the number of windmills in a park and transmission-loss properties (which depend on water depth and bottom type) may cause the detection and masking ranges calculated to vary considerably between different windmill parks.

In this review, we focus on the measurements made by Ingemansson (2003) at the Swedish Utgrunden windmill farm (Table 1, Fig. 5a), since he not only measured the acoustic pressure but also the ambient noise, acceleration (Fig. 5b), and transmission-loss

Table 1. Properties of windmills from which underwater sounds have been recorded. Nogersund, Bockstigen, Gotland and Utgrunden are located in the Swedish Baltic Sea; Vindeby is located in the Danish Baltic archipelago. na: not available

Location	Power (MW)	Manufacturer	Fundament	Depth (m)	Source
Nogersund	0.2	Windworld	Tripod	5–15	Westerberg (1994)
Vindeby	0.5	Bonus	Concrete	na	Degn (2000)
Bockstigen	0.5	Windworld	Monopile	6–17	Degn (2000), Fristedt et al. (2001)
Utgrunden	1.4	GE Wind	Monopile	5–10	Ingemansson (2003)

properties of the windmill farm, all of which are useful in evaluating its effects upon fish. In addition, Ingemansson's (2003) measurements were of much higher intensities than those of the other 3 studies, so that if his data reveal no effect on fish, then it is unlikely that the windmill farms examined in the other studies would have had an effect. The following analysis incorporates the transmission-loss measurements of Ingemansson (2003). Even though this transmission loss may be frequency-dependent, we believe that this effect is probably small within the depth and frequency range of interest here (~20 m and ≤1 kHz).

Detection distance

The question as to at what distance fish may hear the sounds of a windmill is very difficult to answer. As already stated, the parameters required to calculate the detection distance of a signal against a noisy background are poorly known for fish.

We used a custom-built Matlab (MathWorks) computer programme to estimate how different hearing abilities and critical bands affect the detection range. The programme estimates the perceived signal-to-noise ratio 1 m from the windmill by the fish. The received sound level of the windmill is calculated as the sum of the intensity of each tonal component and the adjacent broadband noise within the corresponding critical bands (using existing data and extrapolating with the assumption of a constant Q-filter bandwidth). The sound level is then back-calculated to a distance of 1 m using measurements of transmission loss, giving the source level. The source level is compared to the ambient noise level integrated over the critical band (Eqs. 1 & 3). If the hearing threshold of the species and frequency of interest is higher than the integrated ambient-noise level, a comparison is made between the source level and the hearing threshold (Eq. 4). The calculation is repeated over the entire frequency-band within the hearing range of Atlantic salmon *Salmo salar*, cod *Gadus morhua* and goldfish *Carassius auratus.* For the maximum signal-to-noise ratio, the distance is calculated at which the signal would be reduced to ambient noise level. This distance is defined as the detection distance.

It should be emphasised that the results of these calculations are not of higher quality than the input data which, as already stated, contains many inaccuracies, contradictions and a low number of replications. The results should therefore be viewed and used with exceptional caution.

The acoustic spectral density reported by Ingemansson (2003) for the Utgrunden windmill at a wind speed of 13 m s^{-1} is shown in Fig. 5a. The measured spectra

can be compared with the fish audiogram in Fig. 2b. The maximum received sound level in the frequency range of interest for fish hearing is a 180 Hz tonal component (the 50 Hz tonal component is an artifact of the measurement system). In addition, there is a broadband noise component from the windmill in the frequency range around the tonal component (Fig. 5a).

It is difficult to measure ambient noise without problems caused by electrical self-noise interference arising from the recording equipment. In Fig. 5a, the problem of electrical noise is apparent in the 50 Hz frequency band, where there is a peak in the ambient noise spectrum that was probably caused by interference of equipment using 50 Hz AC currents. The question arises as to whether the ambient noise level measurements of Ingemansson (2003) in other frequency bands were also affected by electrical noise; however, the measured ambient noise levels are similar to standard ambient noise curves measured in deep waters by Wenz (1962) and in shallow waters by Piggott (1964). In addition, Ingamansson (2003) measured increased ambient noise in the whole frequency band with increased wind speed. Such an increase is not expected if electrical interference dominates the recordings. We therefore believe that Ingemansson's (2003) data were not significantly affected by electrical interference, except around 50 Hz.

To calculate the detection range, we first calculated the windmill sound level to a 1 m range[3], using the transmission loss of 4 dB per distance doubling (or 13 $\log_{10} r$) measured by Ingemansson (2003). The sound level measurements were made at a distance of 83 m. This rendered a transmission loss of $TL = 13 \log_{10} 83 = 25$ dB from a 1 m range from the windmill to the hydrophone (note that sound absorbtion can be ignored at the frequencies and distances of interest here). This measurement was made at a distance of 83 m. The received level of the tonal component from the windmill was 126 dB re 1 µPa. This component therefore has a source level of 126 + 25 = 151 dB re 1 µPa at 1 m at a wind speed of 13 m s^{-1} and at a frequency of 180 Hz. In a similar manner, we calculated the noise component from the windmill to be 117 dB re 1 µPa Hz$^{-1/2}$ at 1 m around 180 Hz. At this frequency, the measured power spectral density of the ambient noise was 82 dB re 1 µPa Hz$^{-1/2}$ (Fig. 5a).

For cod, the critical bandwidth at 180 Hz is about 72 to 91 Hz (Hawkins & Chapman 1975). We estimate that the received ambient noise level at a wind speed of 13 m s^{-1} is $82 + 10\log_{10}(BW) = 101$ or 102 dB re 1 µPa

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[3]The back-calculation is made from far-field measurements, and as the 1 m range may be within the near-field of the windmill the actual sound level at 1 m distance may differ from the calculated source level (see Footnote[1])

for cod, depending on the choice of critical bandwidth. Note that even though there is a 19 Hz difference between the 2 critical band measurements, this only implies a 1 dB difference in the received noise level. The windmill noise component is integrated over the filtering bandwidth (as is the ambient noise) and added to the tonal component, which should not be integrated over the filter bandwidth. This renders a total windmill signal intensity of 151 dB re 1 µPa received by the fish in this frequency band (the windmill noise component is too weak compared to the tonal component to contribute significantly to the total sound intensity). The signal-to-noise ratio 1 m from the windmill is, at best, 151 to 101 = 50 dB. We can assume that the maximum distance at which the fish can detect the windmill is where the perceived ambient noise equals the sound from the windmill[4]. This gives the fish a maximum detectable distance from the windmill farm of $10^{50/13}$ = 7 km, with a transmission loss of $TL(r) = 13 \log (r)$.

A similar calculation using sound level and noise level data for a wind speed of 8 m s^{-1} gives a maximum detectable distance of 13 km. In this case, the highest signal-to-noise ratio is obtained around 63 Hz, where the critical band width for cod is 56.

This procedure was repeated for data from wind speeds at 8 to 13 m s^{-1} for 3 species of fish with different hearing abilities, using the computer programme described at the beginning of this subsection. The results are summarised in Table 2 and Fig. 6. For goldfish and cod, the detection threshold is limited by ambient noise, and for Atlantic salmon by the hearing threshold. At higher wind speeds the sound from the windmill increases, and the detection range for Atlantic salmon also increases somewhat. Ambient noise increases more than the windmill sounds, and therefore the detection range decreases for goldfish and cod at increased wind speeds (Table 2).

These calculations assume that the signals are detected up to the distance where the signal energy equals the ambient noise level. It may be more realistic to say that fish needs a somewhat larger signal-to-noise ratio to detect the windmill in the background noise, so the real detection distance may be considerably shorter than those reported here. If we arbitrarily assume that a signal-to-noise ratio of 10 dB is needed for a cod to detect the windmills, the detection distance for cod decreases to 1.5 and 2 km for wind speeds of 8 and 13 m s^{-1}, respectively.

On top of this, our analysis does not take into account the fact that directional hearing improves the signal

Table 2. Estimated detection distance of windmills and best detection frequency of fish with different hearing abilities. Assumptions of the model are given in 'Predicting fish reactions to windmill sounds—Noise from windmills'. Detection distances are given for a hearing specialist (goldfish *Carassius auratus*), a generalist (cod *Gadus morhua*) and a nonspecialist (Atlantic salmon *Salmo salar*)

Wind speed (m s^{-1})	Goldfish	Cod	Atlantic salmon
8	63 Hz / 25 km	63 Hz / 13 km	100 Hz / 0.4 km
13	180 Hz / 15 km	180 Hz / 7 km	100 Hz / 0.5 km

detection capabilities of those fish limited by received ambient noise. For the measurements at 8 and 13 m s^{-1} in Table 1, the detection thresholds of goldfish and cod are ambient-noise-limited, whereas that of Atlantic salmon is hearing-threshold-limited. Directional hearing is therefore predicted to benefit the detection of windmill noise by goldfish and cod, whereas Atlantic salmon is not has no such benefit. With an arbitrarily chosen receiver-directionality index of 10 dB, the cod's detection range is improved to 38 and 51 km at 8 and 13 m s^{-1}, respectively, assuming a detection threshold of 0 dB.

In addition to the problem of quantifying the detection threshold and receiver directionality, the assumptions behind the above calculations are uncertain, especially when the detection range is large. There are several sources of excessive transmission loss at long ranges, such as variations in acoustic impedance, inhomogeneities of the medium and multi-path interference. In addition, the intensity of ambient noise varies with the intensity of shipping and with weather conditions (e.g. in the presence of rain: Urick 1983, NRC 2003). Variations in ambient noise would significantly change the detection distance calculated here.

Finally, it should be noted that the above calculations were made using units of sound pressure level, and the result is therefore only valid for fish possessing a swim bladder. For those without a swim bladder, hearing sensitivity is much less (Fig. 2b), and the critical bandwidths of the hearing system seem to be much wider. The relevant cue for fish with no swim bladder is particle displacement rather than acoustic pressure. An extrapolation to fish with no swim bladder is therefore only valid in the free acoustic field.

The relevance of detection distance per se is that this is the distance at which a wind farm may influence the choice of swimming direction of an approaching fish. The role of acoustic information in fish orientation is so far essentially unknown, but acoustic cues for navigation have been proposed by, for example, Enger et al. (1989).

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[4] Herein, 'ambient noise' is either the perceived background noise level from the ocean, or the hearing threshold of the fish, whichever is highest
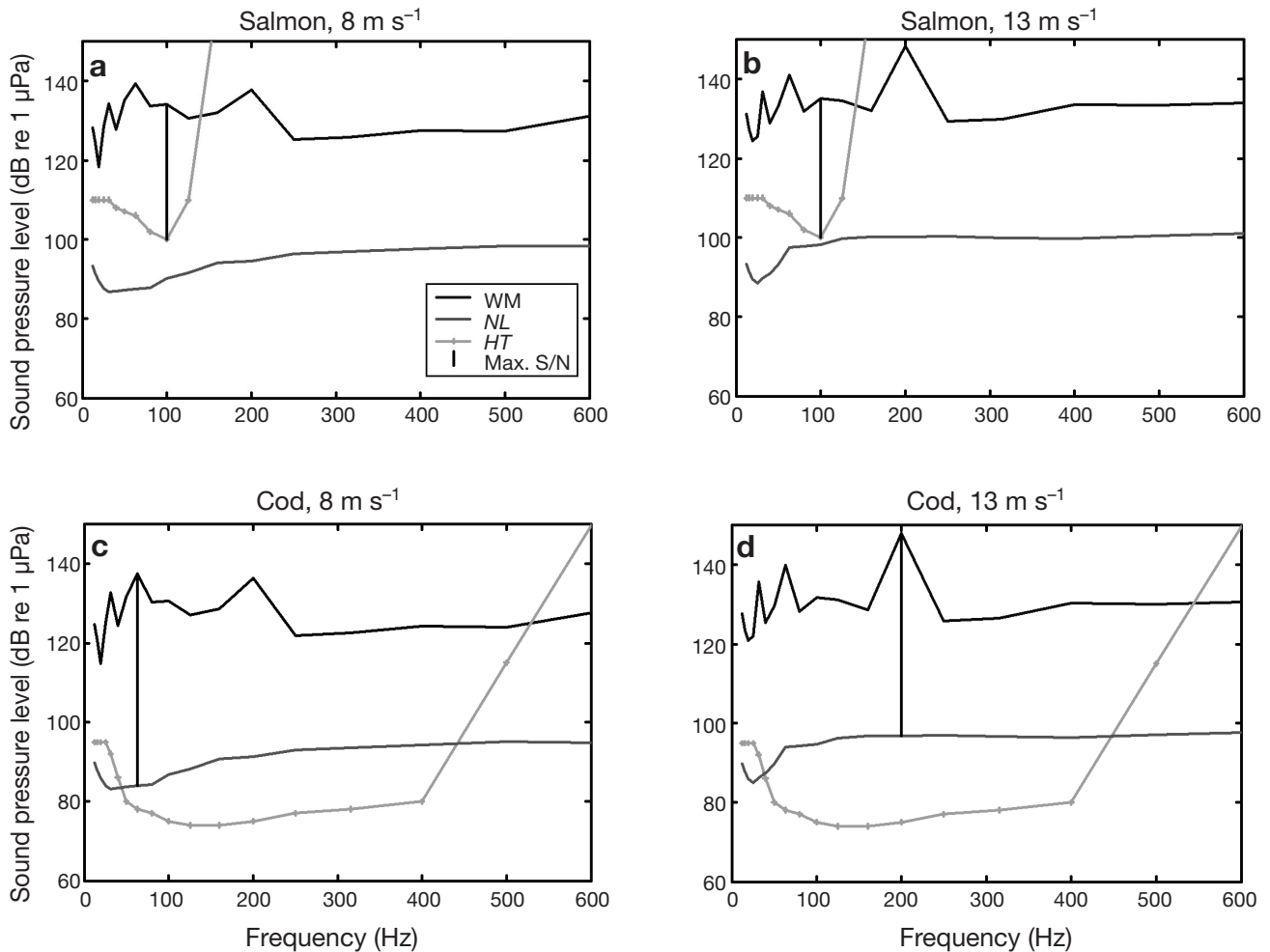
Fig. 6. *Salmo salar and Gadus morhua.* Computer modelling of detection distance of a windmill by Atlantic salmon and cod. WM: windmill noise, with tonal and broadband components summed and back-calculated to 1 m from the windmill; *NL*: received noise level (including effect of critical band estimates); *HT*: hearing threshold of fish. Wind speed is 8 m s^{-1} in (a) and (c), and 13 m s^{-1} in (b) and (d). Vertical line: best signal-to-noise ratio (S/N, at 1 m). Windmill data from Ingemansson (2003); Atlantic salmon hearing data from Hawkins & Johnstone (1978); and cod hearing data from Hawkins & Chapman (1975)

Masking

As noted, fish produce a variety of sound for communication. To determine whether windmill noise reduces the distance over which fish can communicate, we need to know how loud fish calls are. There are only a few such measurements known to us: A. D. Hawkins (pers. comm.) measured the source level of grunts from haddock *Melanogrammus aeglefinnus* as 114 to 120 dB re 1 µPa. The frequency range of these grunts is ~200 to 500 Hz (Fig. 7). This is similar to the frequency content of the windmill sounds. Haddock is a member of the cod family, and even though its hearing abilities have not been investigated we assume they are similar to those of the cod *Gadus morhua*. The bandwidth of the communication signal (300 Hz) covers several of the critical bandwidths of cod. In estimat-

ing the detection distance of these signals, it can therefore be assumed that the noise is perceived with a bandwidth equal to the signal bandwidth, or 10 log$_{10}$ (300) = 25 dB. The ambient noise level at these frequencies at a wind speed of 13 m s^{-1} is about 82 dB re 1 µPa Hz$^{-1/2}$ (Fig. 5a). The perceived ambient noise level of the haddock at 13 m s^{-1} is thus 82 + 25 = 107 dB re 1 µPa. The signal-to-noise ratio 1 m in front of the haddock would be, at best 120 to 107 dB = 13 dB. Assuming a detection threshold of 0 dB, the sound would be audible to another haddock at a maximum distance of 10$^{13/20}$ = 4 m. Here we assume spherical dissipation loss of the communication signals rather than the 13 log *r* used for the windmill signals, as the distance between the 2 fish is very short. At lower wind speeds, the reduction in detection distance caused by windmills would be smaller. The detection threshold is
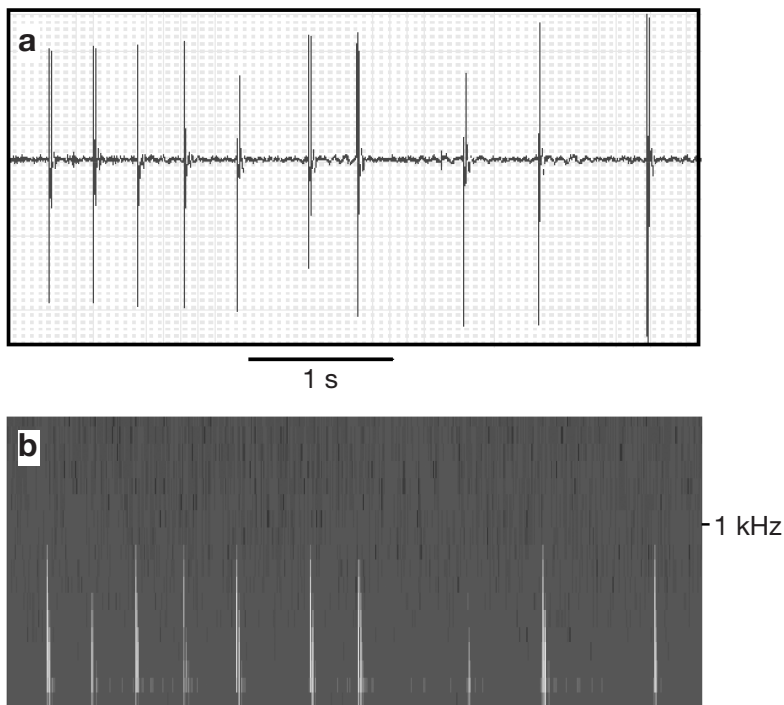
Fig. 7. *Melanogrammus aeglefinus*. Sounds recorded from haddock (from A. V. Soldal & B. Totland pers. comm.) presented as an oscillogram (top panel, sampling frequency 5.5 kHz), and a spectrogram (bottom panel, filter bandwidth 172 Hz, Blackmann-Harris window)

also improved by the directional hearing capabilities of the haddock. Again, these calculations may be erroneous, as haddock register particle displacement rather than the acoustic pressure component at close range. Also, caution must be used in interpretation of these values, as the data from which they are calculated are prone to great inaccuracies and variations.

Within distances at which the windmill sound is louder than the ambient noise (up to 25 km in Table 2), the detection range of the haddock calls is reduced. This range is most probably the maximum at which windmills may mask acoustic communication signals of any fish species. The decrease in detection range due to an increase in ambient noise can be modelled with the sonar equation. This so-called 'range-reduction' factor is a function of the nature of the transmission loss and the increase in noise level, but is not a function of the detection threshold of an animal (Møhl 1981). Thus, under spherical spreading conditions, an increase of 6 dB in the detected ambient noise level would decrease the detectable range by a factor of 2. The advantage of this approach is that conclusions may be drawn without any prior knowledge of the detection threshold of an animal.

Nevertheless, behavioural studies are needed to determine the absolute detection range and to evaluate whether or not the range-reduction factor has any

significant implications for the behaviour and survival of a fish. For haddock, acoustic signals are an important component of its spawning behaviour, and this is probably true for other members of the cod family as well (Hawkins & Rasmusssen 1978). A significant reduction in the distance at which such signals are possible could, in a worst-case scenario, make spawning impossible. We know too little about fish bioacoustics to evaluate if such a masking of signals would pose a significant problem for the reproductive behaviour of fish.

Consistent avoidance response

To estimate the maximum distance of avoidance response by fish to windmill sounds, even more assumptions are required than those for calculating the detection ranges. Even at 1 m distance, the sound levels of the windmills at Utgrunden are not sufficiently high to consistently frighten off Atlantic salmon *Salmo salar* or eels *Anguilla anguilla* (Sand et al. 2001). However, at frequencies below 20 Hz, fish seem to be affected by the acceleration component rather than by the pressure component of the acoustic field. The acceleration component of the sound field was not measured by Ingemansson (2003). When close to a sound source, it can not be directly inferred from the pressure measurement.

However, the acceleration measurements made on the windmill tower by Ingemansson (2003) can be used to assess the maximum particle acceleration induced by the tower in the medium. The maximum acceleration is about 0.5 m s^{-2} for frequencies below 20 Hz (Fig. 5b). It seems that at least Atlantic salmon *Salmo salar* (and possibly many other fish species) are only consistently frightened away from sound sources that induce acceleration larger than ~0.01 m s^{-2}.

At what distance is particle acceleration of maximum 0.5 m s^{-2} reduced to the threshold that consistently frightens away fish (0.01 m s^{-2})? The rate of decrease in particle acceleration close to a sound source depends on whether the source is a monopole (pulsating) or dipole (vibrating) sound radiator (Beranek 1983), and also on water depth (Medwin & Clay 1998). The accelerometer measurements in Fig. 5b indicate that vibrations occur both radially and tangentially to the tower. The tangential acceleration indicates a dipole mode of vibration, the radial acceleration either a

monopole or a dipole mode. It seems more conceivable from a mechanical point of view that the windmill vibrates like a dipole rather than like a monopole. In a free sound field, the vibrations generated by local flow around a monopole sound source drop according to $40 \log_{10} r$ (Kalmijn 1988), and the critical range at which the flow falls below 0.01 m s^{-2} is 7 m. If the sound-generation mechanism is a dipole, the acceleration falls off as $60 \log_{10} r$ (Kalmijn 1988), and the critical range is reduced to 4 m. These calculations are only valid in a free acoustic field and the critical ranges may be considerably longer in shallow water. Also, the calculations assume that Ingemansson's (2003) measurements were made in the direction of maximum acceleration; this has to be confirmed by further measurements.

Again, it should be emphasised that great caution is needed in interpreting these calculations. The calculations were made on data of often very low quality and from experiments with little or no replication. Measurements of the acceleration component of the acoustic field around windmills are necessary to make a more accurate assessment of distances at which fish are frightened away by the windmills sounds.

Risk of hearing loss

Even within 10 m from the windmill, the source level of windmill noise is much lower than the levels shown to cause temporary and permanent hearing loss in fish. However, 2 important caveats need to be considered. First, most of the studies on how fish ears are damaged by noise do not indicate whether or not hearing in fish may be affected by exposure to stimuli of lower intensity than those used in the respective experiments. Second, to our knowledge there have been very few studies on the long-term effects of noise on hearing in fish. At present there is no data to evaluate whether windmill noise may induce hearing loss in fish at close range during exposure over extended periods of time.

Conditioning and habituation

Fay (1998) argued that goldfish may perceive sound in a similar manner to humans, i.e. they may use background noise information to obtain an 'acoustic scene' of the surroundings (sensu Bregman 1990). Therefore, fish may be able to associate the sound from windmills with a structure not representing any danger, and therefore to a signal that may be disregarded. This would result in habituation to windmill sounds. The effects of habituation are very difficult to study in field situations, but are likewise very important when eval-

uating the effects of anthropogenic noise on wildlife.

Even though fish may detect the sound from windmills at relatively long distances, this may not causing any stress or reduce their survival chances. This is of course only true if the sounds from the windmills are not loud enough to damage their inner ears, and if sound communication and predator and prey detection by acoustic means is not masked by the sounds from the windmills.

On the other hand, fish may be affected by noise even though they become rapidly habituated to it, and even though no physiological damage is visible. Stress may be induced from not being able to detect sounds from the auditory scene around the fish, which could result in reduced survival abilities. With the current knowledge on hearing in fish, it can not be concluded whether or not windmill noise may have such effects on fish.

CONCLUSIONS

This review has evaluated the possible effect on fish of underwater noise from windmills. We predict that goldfish, Atlantic salmon and cod can detect offshore windmills at a maximum distance of about 0.4 to 25 km at wind speeds of 8 and 13 m s^{-1}. These detection distances may vary substantially as a function of wind speed as well as type and number of windmills, water depth and bottom substrate. We could find no evidence that windmills cause temporal or permanent hearing loss in fish even at a distance of a few metres. The windmills produce sound intensities that may cause permanent avoidance by fish within ranges of ~4 m, but only at high wind speeds (13 m s^{-1}). The windmill noise may have a significant impact on the maximum acoustic signalling distances by fish within a range of a few tens of kilometres. It is not known to what degree this actually reduces the fitness of the fish.

Hearing in fish is a complicated mixture of particle acceleration and acoustic pressure. Few data exist either on windmill underwater noise or on how fish are affected by anthropogenic noise. Our conclusions were reached using data on windmill sounds from a single location on the Swedish Baltic coast. Any extrapolation to other areas and windmill parks should be made with great caution.

During construction of wind farms, additional noise (e.g. from pile-driving) may have much more significant effects on fish than those reported here (Hoffmann et al. 2000). The present review is concerned only with noise connected with windmill operations. It is important, however, to incorporate possible disturbances during their construction for an environmental evaluation of the effects of wind farms on fish.

Shipping induces considerably higher sound intensities than windmills (cf. present Fig. 5a with figures in NRC 2003). In considering the overall underwater ambient noise level, the effects of shipping must therefore be included. However, the transient nature of ship noise makes comparison with windfarm noise difficult.

A more careful evaluation on the effects of windmill noise on fish is only possible with better data on the nature of the acoustic field around windmills (including measurements of the particle velocity component of the sound field) and with a better understanding of the behavioural and physiological reactions of fish to the sounds of windmills.

If future studies should show that windmill noise affects fish behaviour, underwater noise could be reduced through alternative windmill fundaments, or by fitting sound-dampening materials around the windmill towers.

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