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Impact of naval sonar signals on Atlantic herring (*Clupea harengus*) during summer feeding

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Naval anti-submarine sonars produce intense sounds within the hearing range of Atlantic herring (*Clupea harengus*). In this study, schools of Atlantic herring were exposed to sonar signals of 1–2 kHz (low-frequency active sonar, LFAS) and 6–7 kHz (mid-frequency active sonar, MFAS) and playbacks of killer whale feeding sounds during their summer feeding migration in the Norwegian Sea. The fish schools neither significantly dived nor changed their packing density in response to the LFAS and MFAS transmissions received by the fish at estimated sound pressure levels (*SPLs*; RMS) up to 176 and 157 dB re 1 μPa and estimated cumulative sound exposure levels up to 181 and 162 dB re 1 μPa^2 s, respectively. In contrast, killer whale feeding sounds induced diving responses at received *SPLs* at ~150 dB re 1 μPa. Herring behaviour was studied by using a 116-kHz hull mounted fishery sonar. This seems a promising method for studying the behaviour of free-ranging fish in situations in which other methods are difficult to use, such as migrating schools and fish close to the surface.

Keywords: Atlantic herring, behaviour, naval sonar, sound exposure.

Introduction

Levels of anthropogenic sound in the ocean have increased during the past decades as a consequence of increased ship traffic, oil and gas exploitation, underwater construction, and military activities (reviewed by Southall *et al.*, 2007; Slabbekoorn *et al.*, 2010). Consequently, an important topic in marine science, currently with a main focus on marine mammals (e.g. Richardson *et al.*, 1995; Southall *et al.*, 2007), is how these sounds might affect marine animals. Sound is also important to fish, which use it for communication (Bass and McKibben, 2003), orientation and habitat selection (Simpson *et al.*, 2004), and perceiving their surroundings (Sand and Karlsen, 2000; Popper *et al.*, 2003).

Exposure of fish to intense sounds has been shown to result in temporary hearing loss (Smith *et al.*, 2004; Popper *et al.*, 2007) and physiological injury (Popper and Hastings, 2009). Additionally, anthropogenic sounds may cause behavioural changes, such as avoidance of the exposed habitat (Engås *et al.*, 1996; Slotte *et al.*, 2004) at lower levels. From a conservation perspective, behavioural effects could be most critical, as these may influence life cycle processes like migrations, and thus in the worst case harm the stock, or they may affect the ecosystem by altering the predator–prey balance (Lima and Dill, 1990).

Atlantic herring (*Clupea harengus*) form aggregations that are among the largest of pelagic fish in the Northeast Atlantic. They are the principal prey for many species in the Norwegian Sea (Holst *et al.*, 2004) and are the target of a large fishery industry (Hamre, 1990). The life history of Atlantic herring is highly seasonal and is divided into three main phases: overwintering in October–January; spawning in February–March; and feeding in May–September, linked through well-defined migrations (Holst *et al.*, 2004). In addition to being separated in time and space, these different phases exhibit large variations in behaviour and responsiveness of Atlantic herring. For example, Nøttestad *et al.* (1996) found pronounced differences in schooling dynamics and predator awareness between the non-feeding stage before spawning and during the early feeding stage just after the spawning of Atlantic herring. After spawning and before the onset of their main feeding phase, the Atlantic herring reach their lowest energetic condition of the year (Holst, 1996). Since the ability to cope with stress decreases with the animals' condition (McEwen and Wingfield, 2003), this is a phase when the Atlantic herring is highly vulnerable to stress such as sound disturbance.

Hearing ability varies between species, and most teleost fish have a hearing range limited to frequencies below 500 Hz (e.g. Chapman and Hawkins, 1973; Hawkins and Johnstone, 1978; Mann *et al.*, 1998). Clupeid fish such as the Atlantic herring can detect frequencies up to at least 4 kHz (Enger, 1967), but with higher thresholds than at lower frequencies. Modern naval, long-range, active-sonar systems typically transmit signals in the 1–10 kHz frequency range (Ainslie, 2010), thus partially overlapping with the hearing range of Atlantic herring. For the purposes of fisheries management and environmental regulation, it is important to understand how sound disturbances may affect fish behaviour to establish regulations and sonar operation procedures that will minimize potential negative impact on marine ecosystems.

In November 2006, a controlled exposure experiment was conducted on high-density concentrations of overwintering Atlantic herring in northern Norway, finding no significant behavioural reactions to sonar transmission in the 1–7-kHz frequency range (Doksæter *et al.*, 2009). Similarly, experiments with Atlantic herring in net pens exposed to 1–2 kHz sonar signals in different seasons also did not cause any avoidance reactions (Doksæter *et al.*, 2012). Such captivity experiments are very useful to detect small-scale changes in behaviour as well as identify levels that trigger the onset of a reaction, but a reaction might be influenced by the captive situation. To enable a generalization of the results, an *in situ* field experiment during summer feeding was needed.

The objective of the present study was to conduct an *in situ* experiment on post-spawning Atlantic herring in May during their westward summer migration to the feeding grounds. The results are compared with those from a similar experiment on *in situ* overwintering Atlantic herring (Doksæter *et al.*, 2009).

Methods

Controlled exposure experiments were conducted on 23 and 24 May 2008 in the coastal region of the Norwegian Sea, near 69°N 12–14°E, ~100 km west of Andøya in northern Norway just outside the continental shelf break, with bottom depths >1000 m. The experiments were conducted using the FFI research vessel "H. U. Sverdrup II", hereafter "Sverdrup", and the commercial purse-seine fishing vessel "Nybo".

Experimental procedure

The behaviour of schools of Atlantic herring was monitored from "Nybo", which remained stationary, using a 116-kHz omnidirectional sonar (Simrad SH80, Kongsberg Maritime, Norway). "Sverdrup" passed near the schools, towing a naval sonar source [SOCRATES, Netherlands Organisation for Applied Scientific Research (TNO), the Hague, the Netherlands]. Each school was exposed to three different experimental treatments; transmissions of low-frequency (1–2 kHz sweeps) active sonar (LFAS) signals, mid-frequency (6–7 kHz sweeps) active sonar (MFAS) signals, and control (SOCRATES towed without transmitting). The signals are described below. The purpose of the control was to distinguish the possible effect of a sonar transmission from the possible disruption caused by the source vessel and towed body itself. The experiment was conducted as a block design, each block consisting of three runs with treatments (control/LFAS/MFAS) in randomized order. A "run" is one pass of a school with one treatment. To avoid habituation, sequential blocks targeted different schools.

Before each block, "Nybo" located a new school and then maintained a distance of ~200 m using the target-tracking function of the SH80, which automatically adjusts the beams to follow the school. Before each run, "Nybo" estimated the position of the school and "Sverdrup" plotted a course with a closest point of approach (CPA) from the school of 50–100 m. During each run, "Sverdrup" maintained a speed of ~4 m s^{-1} (8 knots) and transited 1.85 km (1 nautical mile, 1852 m) to either side of the school, transmitting LFAS/MFAS/control. After finishing a block, "Nybo" stopped tracking that school and located a new school for the next block. Measurements were conducted between 8 p.m. and 5 a.m. local time (UTC + 2 h) when the herring was organized into dense schools.

Background noise

To estimate the ability of an animal to hear a signal in a background of broadband noise, the unmasked hearing threshold and the critical ratio (CR) are important parameters. The CR is defined for a narrowband signal in broadband masking noise as the difference in the level between a just-audible signal and the noise spectral density. The CR, so defined, can be thought of as the bandwidth of a hypothetical rectangular auditory filter, expressed in decibels (Au, 1993). The unmasked hearing thresholds of Atlantic herring have been measured using electrophysiological techniques (Enger, 1967), but no measurements are known to the authors of the CR for Atlantic herring. CRs for cod have been measured for frequencies up to 380 Hz (Chapman and Hawkins, 1973; Figure 1), and based on these data, we estimated the following linear relationship

$$CR = 10\,\log_{10}\frac{f}{2}, \tag{1}$$

where f is the acoustic frequency (in Hz). The ambient noise is assumed to be dominated by noise from "Nybo" and "Sverdrup" close to the vessels and by wind-generated noise elsewhere. Windspeed for 23 and 24 May was 3–7 m s^{-1}, air temperature of 2–4°C, and the sea surface temperature was 7°C. The contribution from wind noise is estimated using the deep-water approximation of Ainslie (2010; eq. 9.154 and 8.206), with the maximum measured wind speed of 7 m s^{-1}, and unstable sea surface conditions due to the measured temperature of the water being higher than in the air (Figure 2a).

The ship noise was measured 150 m behind "Sverdrup" (Figure 2a) using the TNO Delphinus towed hydrophone array (Kvadsheim *et al.*, 2009) which was deployed immediately after the exposure runs. The hydrophone array contains 16 single hydrophones, and the noise level given was the average of these. The array was towed at 33-m depth, thus coinciding with the distribution depth of the herring. The minimum audible signal to the fish in broadband noise is calculated from the CR [using Equation (1) to extrapolate the measurements to the higher frequencies of interest] and the estimated noise levels.

Exposure to naval sonar transmissions

In all runs, SOCRATES was towed at a depth of 55 m. The LFAS and MFAS signals were hyperbolic up-sweeps with 1 s durations and 20 s pulse intervals (see Figure 2 in Doksæter *et al.*, 2009), transmitted omnidirectionally. Source levels (*SLs*) as defined by

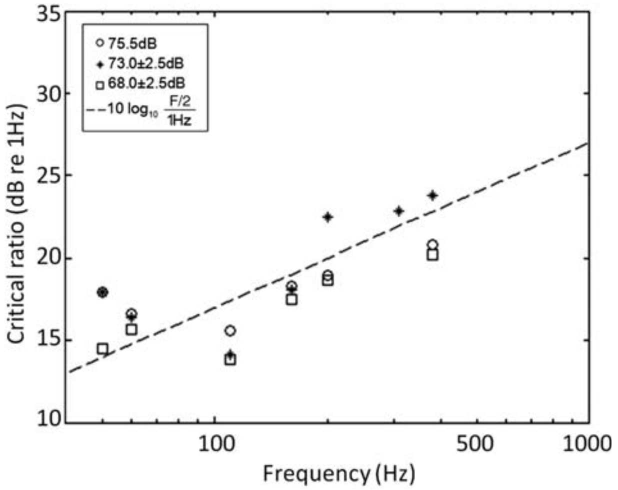

Figure 1. Measurements of CR in cod at different levels of background noise; >75.5 dB re 1 μPa^2 Hz^{-1} (circles), 73.0 dB re 1 μPa^2 Hz^{-1} $\pm$ 2.5 dB (asterisks) and 68.0 re 1 μPa^2 Hz^{-1} $\pm$ 2.5 dB (squares); from Chapman and Hawkins (1973). The dashed line is the linear fit given in Equation (1) to enable extrapolation to frequencies of interest.

Morfey (2001) and Ainslie (2010) were 214 and 195 dB re 1 μPa m for LFAS and MFAS, respectively. As a precaution for marine mammals in the area, the *SL*s were gradually increased, over 10 min, from 152 and 158 dB re 1 μPa m to full power before each run for LFAS and MFAS, respectively.

Exposure to playbacks of killer whale feeding sounds

In addition to the LFAS/MFAS transmissions, Atlantic herring were exposed to playbacks of killer whale feeding sounds. These sounds were recorded using a digital acoustic-recording tag (*D*-tag; Johnson and Tyack, 2003) attached to the killer whales (Shapiro, 2008). The tagged killer whales were feeding on Atlantic herring close to the study site. These sounds were projected from an underwater speaker (LL916, Lubell Labs, OH, USA), lowered into the school, from a small boat to a depth of 25 m.

Sounds of killer whales surfacing were omitted from the record, and low-frequency flow noise was reduced by highpass filtering at 800 Hz. The D-tag has a flat frequency response to 45 kHz, and the speaker has a response ± 8 dB from 600 Hz to 20 kHz. Consequently, the reproduced killer whale feeding sounds included typical pulsed calls, echolocation clicks, and tail slaps (Shapiro, 2008). Because these sounds were effectively bandpass filtered from 800 Hz to 20 kHz, the lower-frequency components were not reproduced. The *SL* values of killer whale feeding sounds were 150–160 dB re 1 μPa m, and thus similar to those of killer whales feeding on salmon (Miller, 2006).

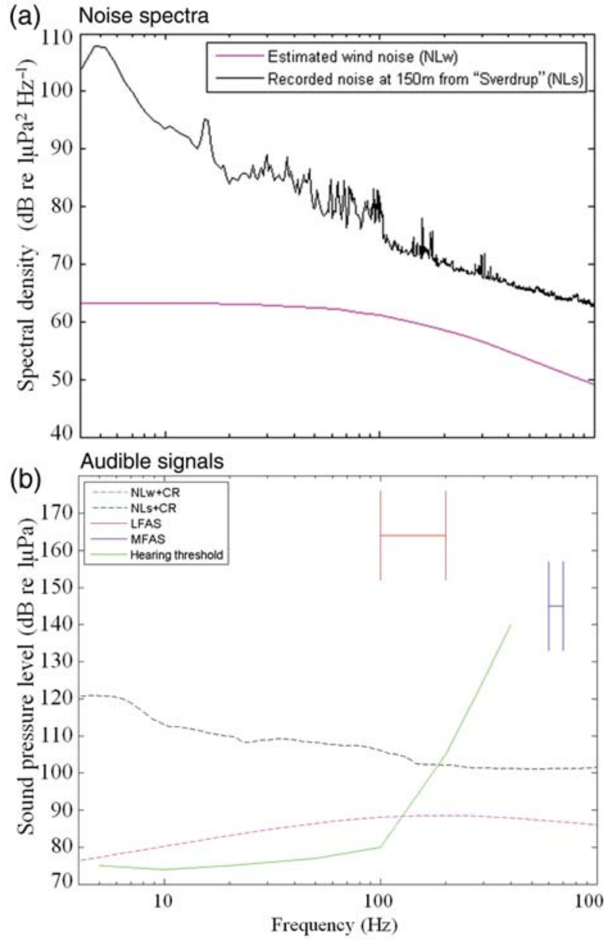

Figure 2. (a) Noise spectral density level of ship noise from "Sverdrup" at 150 m (black line) and estimated wind noise for a windspeed of 7 m s^{-1} (pink line). (b) Dashed lines show the minimum audible signal above ship noise 150 m behind the ship (black) and above ambient noise at 7 m s^{-1} windspeed (pink), using CR extrapolated by Equation (1). The ship noise curve represents the noisiest conditions when the vessel was closest to the herring, around the CPA. The wind noise level represents the highest expected noise conditions in the absence of a vessel. Green curve is the hearing curve of herring (from Enger, 1967). The hearing thresholds likely represent conservative estimates, with the thresholds potentially being lower due to some background noise being present during experiments (Enger, 1967). Bars show the estimated received *SPL*s and frequency range of LFAS (red) and MFAS (blue) transmissions. Horizontal lines indicate frequency range, whereas the vertical span indicates the spread in *SPL* between the start of the run (lowest) and the CPA (highest). This shows that the LFAS transmissions are clearly audible to the herring during the entire run above any background noise. In contrast, MFAS transmissions might not have been audible.

Behavioural measurements

During each run, the behaviour of the herring schools was monitored from "Nybo" using the hull-mounted SH80 high-frequency sonar. The SH80 operator on "Nybo" was blind to the experimental condition (LFAS/MFAS/control).

The mean depth (*D*; m) of the school and a proxy of the backscattered energy from the school (*E*; dB) were calculated vs. time using the SH80 module of the LSSS post-processing software (MAREC, Bergen, Norway; http://www.marec.no). *E* is the mean (uncalibrated) energy across the school given for a fixed volume determined by the sonar beam. Changes in *D* indicate vertical movement in the watercolumn, whereas those in *E* indicate changes in orientation and swimming directions of the fish.

Experimental runs where the returning echoes from the schools were obscured by noise from the wake of "Sverdrup" were discarded and not used in the statistical analysis.

Statistical analyses

Based on previous results on how Atlantic herring react to a gradually increasing sound pressure field, e.g. from an approaching vessel (Vabø *et al.*, 2002; Ona *et al.*, 2007), a potential reaction is assumed to occur in the period between transmission start and maximum exposure at the CPA. When the sound signal is decreasing, Atlantic herring tend to return to their pre-exposed depth and school structures (Vabø *et al.*, 2002; Ona *et al.*, 2007).

The initial D and E vary between runs and blocks, and a direct comparison is thus not possible. Therefore, to evaluate changes in the vertical position and orientational changes of each school in each run and to compare the results between treatments (LFAS, MFAS, and control), the following was done. For each run j in block k, changes in D and E were evaluated using time-series segments comprising 2 min "before" exposure and 2 min "during" maximum exposure, at the CPA ±1 min, resulting in a paired before and during period for each run. Therefore,

$$\mu_{\mathrm{During}\ jk} = \mu_{\mathrm{Before}\ jk} - \delta_{jk}, \tag{2}$$

where μ is the mean for each treatment and δ_{jk} is the difference in D or E. The null hypothesis H_0 is that values for δ_{jk} do not differ between treatments

$$H_0 : \ \delta_{\mathrm{Control}_k} = \delta_{\mathrm{MFAS}_k} = \delta_{\mathrm{LFAS}_k}. \tag{3}$$

The alternative hypothesis H_1 is that either MFAS or LFAS differs from the control

$$H_1 : \ \delta_{\mathrm{Control}} \neq \delta_{\mathrm{LFAS}} \quad \text{or} \quad \delta_{\mathrm{Control}} \neq \delta_{\mathrm{MFAS}}. \tag{4}$$

Avoidance reactions of Atlantic herring may be a change in orientation or swimming direction, or vertical and horizontal avoidance (Pitcher *et al.*, 1996; Nøttestad and Axelsen, 1999), with diving as the most common avoidance response (Nøttestad and Axelsen, 1999).

The expected reaction of sonar exposure is thus an increase in D due to increased diving. Changes in backscattered energy, E, may either increase or decrease depending on the orientation of fish relative to the sonar. As LFAS is well within the hearing range of Atlantic herring, whereas MFAS is not, we expected a stronger reaction to LFAS.

A non-parametric randomization test (Manly, 1997) was used to test H_0 against H_1. This method is robust regardless of any order structure of the treatments, potential autocorrelation of the time-series in the before and during periods and the unequal number of runs under each treatment. Here, RSS_0 is the residual sum of squares in the least-squares fit of the model in Equation (2) to the time-series observations under H_0 and RSS_1 is the residual sum of squares in the least-squares fit under H_1. The statistic used to test H_0 against H_1 is $T = RSS_0 - RSS_1$, where H_0 is rejected for large values of T.

The significance level of the observed value of T can be assessed through the following randomization procedure. Under the null hypothesis, the correspondence between the observed values of δ_{jk} and j within each experiment is random. For each experiment, there are $3! = 6$ possible ways to assign the three pairs of before and during series to the three treatments: control, LFAS, and MFAS. If there are n such experiments, then there are a total of 6^n possible arrangements across the n experiments. The significance level (or p-value) of the observed value t of T is given the proportion of these arrangements for which the value of T exceeds t. As the value of RSS_0 is the same for all these arrangements, it is sufficient use RSS_1 as the test statistic, in which case the p-value is the proportion of arrangements for which RSS_1 is less than its observed value. The same general randomization scheme can be used when, as here, the number of before–during trials under the different treatments varies between experiments.

The killer whale runs were not included in the statistical analysis, as these were conducted differently from those with sonar treatments. More specifically, SOCRATES was towed from a large and noisier ship, compared with the underwater speaker which was lowered from a small boat with its engine off. Also, for the sonar runs, received sound pressure levels (*SPLs*) gradually increased, reached their maxima at the CPA, and then decreased as the vessel departed. In contrast, for the killer whale runs, the fish were abruptly exposed to the maximum *SPL*; period before includes 2 min before the transmissions; and period during includes the first 2 min for the killer whale playback runs.

Calculations of received *SPL* and sound exposure level

Sound speed profiles were estimated from conductivity and temperature vs. depth data collected three times during the experiment (SD204, SAIV AS, Bergen, Norway). These sound speed profiles, in addition to the transmitted frequency, *SL*, directivity and depth of SOCRATES, the mean depth of the measured schools, and the range from SOCRATES to the schools for each transmission, were input to an acoustic propagation model (LYBIN; Hjelmervik *et al.*, 2008) to estimate the received *SPL* for each transmission, which is defined as the level of the RMS pressure in decibels (ANSI, 1994; Morfey, 2001). Similarly, the *SL* is a measure of the RMS pressure in the far field and scaled to a standard reference of 1 m (Morfey, 2001; Ainslie, 2010). The accumulated, un-weighted sound exposure level (*SEL*) for each run was calculated by using the received *SPL* for each transmission during an exposure and the transmission duration.

Results

Eight LFAS–MFAS–control blocks were conducted, totalling 24 runs in all. The data from one MFAS and three control runs were discarded due to excessive noise from "Sverdrup's" wake interfering with the school echo, leaving eight LFAS runs, seven MFAS runs, and five control runs being accepted for analyses. Additionally, three separate killer whale runs on three different schools were conducted.

Herring behaviour

Day- and night-time behaviour of the Atlantic herring were somewhat different, with the fish being more dispersed in diffuse layers close to the surface during daytime hours, while being in dense schools at depths of 20–50 m at night, despite the 24-h daylight condition during the experiments. All runs were conducted between 8 p.m. and 5 a.m. local time (UTC + 2 h), with the fish schools being clearly defined. At other times of the day, the fish were closer to the surface and more dispersed and therefore could not be tracked with the high-frequency fishery sonar. The depth of the centre of the schools of which experiments were conducted on had were on average 31 m, with an average school volume of ~90 m^3. All schools were moving in a north-westerly direction at an average speed of ~0.5 m s^{-1} (1 knot).

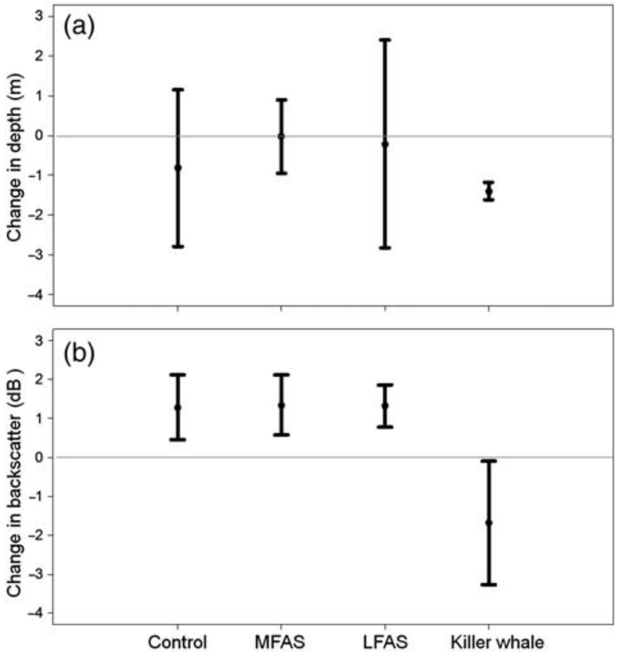

Figure 3. (a) Changes in depth (*D*) and (b) acoustic backscatter (*E*) from a 2-min period before exposure to a 2-min period centred on the CPA. The grey line at zero indicate the D/E before exposure, the dot is the average change around the CPA with bars showing the 95% confidence interval. The minor negative shift in *D* is due to a small increase in mean depth, indicating that the school dove during all exposures, including the no-sonar control. The positive shift in *E* during LFAS, MFAS, and control is due to a decrease in backscattered energy. This is likely due to lateral avoidance, as the lateral TS becomes lower as they turn away from the source ship. The negative shift in *E* during killer whale playback indicates an increase in lateral TS, likely due to a collective diving response.

Herring reactions to sonar transmission and killer whale playback

There were no significant differences in δ_D ($p = 0.41$; Figure 3a), or δ_E ($p = 0.72$; Figure 3b) between the MFAS, LFAS, and control treatments. Therefore, H_0 was not rejected.

Schools did on average move deeper during all three treatments (Figure 3a), indicating diving of the schools as "Sverdrup" passed, independent of whether the sonar was transmitting or not. School backscatter, *E*, decreased during exposure (LFAS/MFAS/Control) compared to the period before exposure (Figure 3b), indicating that the fish changed their orientation or swimming direction as "Sverdrup" passed.

Compared with MFAS, LFAS, and control treatments, the mean δ_D was more negative for the killer whale treatment (Figure 3a), indicating a stronger mean diving response. The backscatter of the school, *E*, increased during exposure to killer whale playback in contrast to the decrease in backscatter during sonar and control exposure. The orientation change was thus different from that for the sonar and control runs.

Estimates of received *SPL* and *SEL*

The shortest distance between SOCRATES and any of the measured schools of Atlantic herring was ~50 m. With an average school depth of 31 m, the Atlantic herring were subject to maximum received *SPL* values of 176 and 157 dB re 1 μPa, and *SEL* values of 181 and 162 dB re 1 μPa^2 s for LFAS and MFAS treatments, respectively (Figure 4). During the killer whale playback experiment, the underwater speaker was lowered directly into the school, and the fish closest to the speaker would hence experience *SPL* of ~150–160 dB re 1 μPa, assuming far-field conditions. The LFAS signal exceeds both the unmasked hearing threshold (Enger, 1967) and the minimum audible signal by at least 45 dB (Figure 2b). Therefore, this signal is expected to be clearly audible to Atlantic herring. The MFAS signal exceeds the minimum audible signal by at least 30 dB, but the hearing

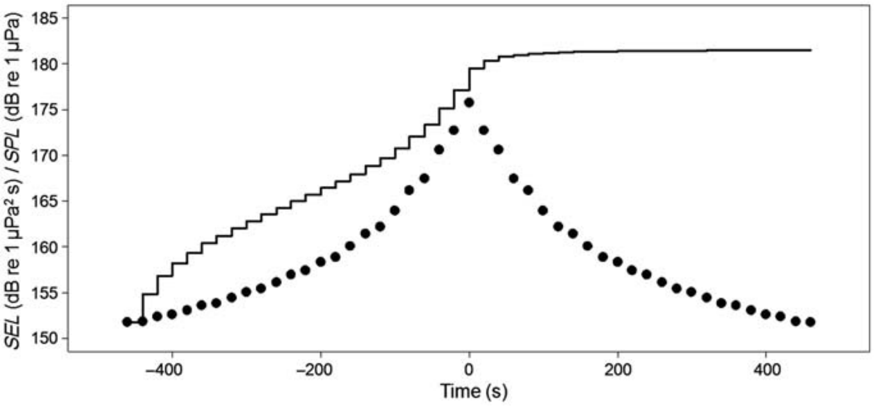

Figure 4. Calculated ping by ping received *SPL* (dB re 1 μPa; points) and accumulated un-weighted *SEL*s (dB re μPa^2 s; line) as a function of time (s) between the fish school and source ship during the LFAS runs. Calculations are based on the estimates of transmission loss as a function of distance from the source to the fish obtained from the acoustic model Lybin, using source characteristics (transmitted levels, frequencies, depth, and directionality) and measured sound speed profiles as input. The conversion from distance to time is based on the geometry of the experiments with the source ship approaching the herring at a constant speed of 8 knots (4 m s^{-1}), transmitting from a distance of 1 nautical mile (1852 m) before to 1 nautical mile after a median CPA of 75 m at time = 0. The herring schools were on average located at 31-m depth, and the calculations are mean values for the depth interval 30–40 m. The corresponding curves for MFAS data will be shifted 19 dB down from these because the MFAS SL is lower by this amount and all other relevant parameters are unchanged.

threshold, if extrapolated above 4 kHz, may exceed the MFAS signal level (Figure 2b). From the available information, it is therefore likely that the MFAS signal is close to the hearing threshold, and it cannot be determined whether the MFAS signal would be audible. The audiogram of Enger (1967) for Atlantic herring indicates that this species has lower hearing thresholds than other clupeid fish (Mann *et al.*, 1998, 2001), but if we used one of these audiograms instead it would not change our conclusion that the LFAS signals were clearly audible to the Atlantic herring.

Discussion

Herring behaviour

Behaviour and distribution of the Atlantic herring varied between day and night, with the fish distributed in relatively stationary diffuse layers close to the surface at daytime, and in dense schools at depths of 20–50 m at night, moving at relatively high speed in a north westerly direction. At night, the school structure suggests a typical migration behaviour with confined and coordinated moving schools (Misund *et al.*, 1997), with the direction indicating that the fish were heading for the westernmost part of the Norwegian Sea, where the main feeding takes place in June–July (Dragesund *et al.*, 1997; Dalpadado *et al.*, 2000). The splitting of schools into surface layers during daytime suggests that surface feeding takes place. Such opportunistic feeding is common during the migration towards the main feeding ground (Nøttestad *et al.*, 1996).

Herring reactions to sonar transmission and killer whale playback

This study has shown that Atlantic herring, during their summer feeding migration, do not respond significantly to naval sonar transmissions in the 1–7-kHz frequency range at the levels tested (*SPL* up to 176 dB re 1 μPa and *SEL* up to 181 dB re 1 μPa^2 s) (Figure 4).

During the LFAS, MFAS, and control treatments, the fish dove somewhat at the time of the CPA (Figure 3a), which is a typical response for Atlantic herring to a passing vessel (Vabø *et al.*, 2002; Skaret *et al.*, 2006; Ona *et al.*, 2007). The mean vertical avoidance (~1 m) is less than that reported for Atlantic herring beneath a vessel (Ona *et al.*, 2007), but is the same as that for other clupeid fish at similar horizontal distances from the vessel (Gerlotto *et al.*, 2004).

The acoustic backscatter decreased somewhat during exposure for all three experimental conditions, including the silent control (Figure 3b). This may be due to lateral avoidance, as the fish became more aligned as they turn away from the source ship. This causes a collective tail-on aspect of the sonar, which reduces the lateral TS (Pedersen *et al.*, 2009), thus decreasing the returning backscatter. Such lateral avoidance has been observed by counting the number of detected schools in the athwartship direction (Soria *et al.*, 1996), and tracking individual fish using split-beam echosounders (Handegard and Tjøstheim, 2005).

The killer whale playback caused the schools to dive (Figure 1), a typical predator-avoidance response by Atlantic herring (Nøttestad and Axelsen, 1999). The observed increase in backscatter may have been caused by this pronounced diving behaviour as fish positioned vertically in a horizontal beam will increase the lateral TS (Pedersen *et al.*, 2009). These reactions were more pronounced than the response to the passing ship, but due to the difference in how the sound was presented, they were not directly comparable. For example, the stronger reaction during killer whale playback compared with the ship approaches may be caused by the presence of the underwater speaker and its cable within the school, the sudden onset of the transmissions, or both. Koslow *et al.* (1995) reported that demersal aggregations of orange roughy (*Hoplostethus atlanticus*) dispersed when a camera was lowered within ~130 m of the aggregations.

The present results of Atlantic herring during summer feeding migration are in agreement with the *in situ* study of overwintering Atlantic herring (Doksæter *et al.*, 2009). These represent two very different phases in terms of distribution, motivation and energetic condition. During overwintering, Atlantic herring stay in dense, deep layers and do not feed, while during summer feeding migration they stay in coordinated schools feeding and migrating close to the surface (Holst *et al.*, 2004 and references herein). Additionally, experiments on Atlantic herring in net-pens have been conducted in all the annual phases (Doksæter *et al.*, 2012). In all three studies, there were no significant behavioural responses to the sonar transmission vs. control treatments. In both *in situ* studies, the fish dove in response to the vessel passage as well as in response to the killer whale playback. In the overwintering experiment, the killer whale playback induced significantly stronger diving responses than the control runs. The overwintering Atlantic herring descended 5–10 m during vessel passage (see Figure 4 in Doksæter *et al.*, 2009), compared with ~1 m in summer (Figure 3a). During the killer whale playback runs, Atlantic herring descended 20–30 m in winter and ~1.5 m in summer. This indicates a stronger response during winter. Other researchers have also observed strong anti-predator behaviour during overwintering (Vabø *et al.*, 2002; Skaret *et al.*, 2006), explained by the predator vigilance increase with time since the last spawning (Nøttestad *et al.*, 1996; Axelsen *et al.*, 2000). In May, after spawning, obtaining new energy reserves is the most important objective, thus feeding is traded off towards being less reactive to predators (Nøttestad *et al.*, 1996).

Experimental methods

Since the schools of Atlantic herring in this study were migrating, their behaviours could not be remotely monitored using a bottom-mounted echosounder as used by Doksæter *et al.* (2009) as well as Ona *et al.* (2007). Instead, their behaviour was measured using an omnidirectional, high-frequency sonar. Such sonars allow school movements to be recorded in three dimensions (Misund *et al.*, 1996) and have been used to study vessel-noise reactions by fish which are horizontally distant from the vessel (Misund *et al.*, 1996; Soria *et al.*, 1996, Gerlotto *et al.*, 2004). These early studies mostly obtained their results from video analyses of the sonar images. With the development of more advanced fish-finding sonars, digital records in the form of swimming speeds and directions and school depths became available and have been applied in studies of migration patterns (Kvamme *et al.*, 2003; Godø *et al.*, 2004). This approach produces outputs similar to an echosounder and was used in the present study to obtain the backscatter and depth data. The depth output gives information of the depth of the centre of mass of the school, whereas the vertical extent of the schools is unknown. Sonar methodology is still advancing, and as has been shown by the present study, it may be an efficient tool to study schooling fish, particularly when the target species are moving in the upper pelagic ocean layer, thus ruling out the use of more established acoustic methods. One drawback of the method is the lack of good calibration techniques, and at the current stage, no fisheries sonar have been calibrated properly. However, in this study, a calibrated sonar was not crucial, since it was the relative difference in backscatter and depth between exposed and not-exposed state that was used. For echosounders on the other hand, calibration is a standard operation conducted before most surveys.

Experiments were conducted only at night-time between ∼8 p.m. and 5 a.m. local time. This was due to the herring being dispersed during daytime, preventing sonar tracking. However, Atlantic herring are most responsive at night (Vabø *et al.*, 2002; Skaret *et al.*, 2006), and the potential for the sonar to trigger a reaction is therefore highest within this period.

There were no significant differences between the sonar and control treatments. However, negative results may have type II error, i.e. accepting H_0 when it should be rejected, and the risk of such errors increase with decreasing sample size. Although the sample size ideally should have been larger, results confirm those of the overwintering study (Doksæter *et al.*, 2009) and the captivity study (Doksæter *et al.*, 2012), thus limiting the possibility of the negative result to be by chance. Additionally, we did observe the fish to react to the vessel and/or the towed body, indicating the method to be adequate to detect a reaction, but this reaction did not differ between the treatments.

Concluding remarks

This study documents that adult Atlantic herring did not show any behavioural response to 1–7 kHz naval sonar signals at received SPL up to 176 dB re 1 μPa and SEL up to 181 dB re 1 μPa^2 s during summer feeding migration. This is in agreement with results from studies on overwintering Atlantic herring (Doksæter *et al.*, 2009) and captive Atlantic herring (Doksæter *et al.*, 2012). Operational naval sonars may have an SL exceeding those tested here, and we cannot exclude the possibility of a behavioural response at levels above the maximum levels tested. However, considering the large horizontal spread of Atlantic herring during summer feeding, covering an estimated 300 000 and 500 000 km^2 in the Norwegian Sea (Holst *et al.*, 2004), in combination with the rapid attenuation of the sonar signal, this will affect a very minor part of the distribution volume of Atlantic herring, causing only a small fraction of the total population to be exposed to levels above those tested here.

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