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Feeding herring schools do not react to seismic air gun surveys

Héctor Peña*, Nils Olav Handegard, and Egil Ona

Institute of Marine Research, Observation Methodology, PO Box 1870, NO-5817, Bergen, Norway

**Corresponding Author: tel: +47 5523 5375, fax: +47 5523 6830, e-mail: hector.pena@imr.no*

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The real-time behaviour of herring schools exposed to a full-scale 3D seismic survey off Vesterålen, northern Norway, was observed using an omnidirectional fisheries sonar. Throughout the study period, the herring swam slowly against the predominant northeast current, with a net displacement along with the current. The mean swimming speed after subtracting the drift velocities was 0.35 m s^{-1}, and the mean response speed in the direction away from the air gun array was 0.22 m s^{-1}. No changes were observed in swimming speed, swimming direction, or school size that could be attributed to the transmitting seismic vessel as it approached from a distance of 27 to 2 km, over a 6 h period. The unexpected lack of a response to the seismic survey was interpreted as a combination of a strong motivation for feeding, a lack of suddenness of the air gun stimulus, and an increased level of tolerance to the seismic shooting.

Keywords: fish behaviour, fisheries sonar, seismic survey.

Introduction

Noise generated by anthropogenic/human activities contributes to the general noise levels in aquatic environments (Wenz, 1962; Hildebrand, 2009), and there is growing concern that this potentially affects marine life (Popper and Hastings, 2009; Slabbekoorn *et al.*, 2010). Seismic air gun surveys represent a major source of anthropogenic underwater noise. In caged fishes exposed to air gun emissions, there have been reports of physical injury (McCauley *et al.*, 2000) and changes in behaviour (Pearson *et al.*, 1992; Hassel *et al.*, 2004). In studies of free-ranging fishes, changes in vertical (Dalen and Knudsen, 1987; Slotte *et al.*, 2004) and large-scale horizontal (Engås *et al.*, 1996) distribution patterns have been observed. However, in a study of inshore and reef species, Wardle *et al.* (2001) found no significant changes in the behaviour of fish exposed to seismic air guns.

An indirect measure of the impact of seismic surveys can be assessed by changes in catch per unit effort in nearby fisheries. Skalski *et al.* (1992) reported a 50% decrease in hook-and-line fisheries, and Engås *et al.* (1996) observed a similar decline in trawl catches of cod and haddock, as well as a 50% and 20% decline in longline catches for haddock and cod, respectively. More recently, Løkkeborg *et al.* (2012) report a moderate decrease in longline catches of haddock and Greenland halibut, but an increase in gillnet catches of redfish and Greenland halibut. This increased vulnerability to gillnet gear was hypothesized to be due to increased swimming activity in response to the air gun survey, which is consistent with the increased swimming speed observed in the case of herring exposed to air gun emissions (Dalen, 1973). The increase in the packing density has been also observed in herring as a response to threats (Pitcher *et al.*, 1996; Nøttestad and Axelsen, 1999).

The hearing system of most fishes is sensitive to sound pressures between 50 Hz and 500 Hz (Ladich and Fay, 2012), which overlaps the predominant frequency range of seismic air gun emissions (10–300 Hz, McCauley *et al.*, 2000). In addition, herring have a physostomous swimbladder that acts like a gas reservoir for the bulla system in the inner ear (Allen *et al.*, 1976), which enables herring to detect the pressure-based component of a sound wave at frequencies of up to 20 kHz, and to maintain a constant hearing capability with depth (Blaxter *et al.*, 1979, Mann *et al.*, 2005). Seismic air gun emissions can be detected by fish at long ranges and, based on startle response thresholds in cod, reaction distances of 5–10 km have been suggested in conditions similar to the present study (Hovem *et al.*, 2012). Long-range (>10 km) detection by herring has not been found in the literature, but due to their good hearing capabilities, it is likely that they are able to detect air gun emissions at similar ranges to cod. Exactly how far from the sound source we can expect reactions from fish also depends on the local sound propagation, which in turn is affected by the physical environment, bottom topography, and bottom substrate (Hovem *et al.*, 2012).

The decision by a fish to respond to a sound stimulus likely depends on the internal state and the behavioural context of the fish as well as the character of the sound exposure, and there is not necessarily a direct link between sound exposure and fish reaction. In the case of fish avoidance to research vessels, no clear relationship has been found between detection (based on perceived sound pressure levels) and reaction (De Robertis and Handegard, 2013). For example, when the reaction to a conventional research vessel was compared with the reaction to a noise-reduced research vessel, no clear relationship between the sound level produced by the vessel and fish reaction was observed; furthermore, herring seem to be particularly reactive while overwintering (Vabø *et al.*, 2002; Ona *et al.*, 2007; Hjellvik *et al.*, 2008) but less so during their feeding season (Fernandes *et al.*, 2000; Doksæter *et al.*, 2012). A review of reactions to vessels can be found in De Robertis and Handegard (2013), and it is likely that these considerations are relevant for exposure to seismic surveys as well.

From a recent review by Popper and Hastings (2009), it is clear that most work on the effect of air gun surveys on free-swimming fishes has been conducted on demersal species. The objective of the present paper was to investigate the response of free-ranging herring schools to the approach of a full-scale seismic air gun survey using an omnidirectional fisheries sonar. Based on the studies reviewed above, we expected herring schools to alter their swimming behaviour (e.g. direction and speed) and/or increase their packing density as the seismic vessel approached.

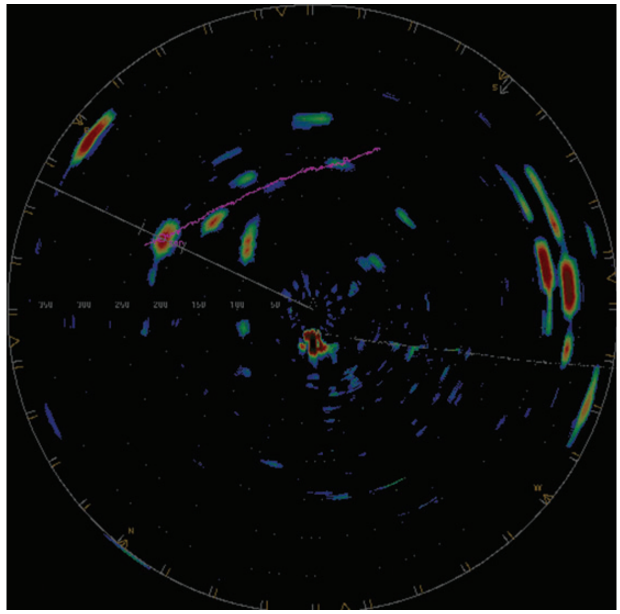

Figure 1. Example of SH80 omnidirectional sonar display. The vessel is in the centre of the image, and the sonar range is 400 m. Herring schools appear as coloured elliptical shapes ranging from green to red. The purple line indicates the direction of one school tracked to the northeast for several minutes.

Material and methods

Experimental set up

This experiment was part of a larger project that aimed to study the effects of 3D seismic shooting on fish distribution and catch rates in Vesterålen, northern Norway during summer 2009 (Løkkeborg *et al.*, 2012). On 29 June 2009, RV "Håkon Mosby" (47.2 m length) left its predefined acoustic survey off northern Norway (69°N, 14°E), and was put into a drifting position with the bow maintained to the southeast, towards the coastline, perpendicular to the first seismic shooting course line in the area. The experiment lasted from 09:42 to 15:02 UTC, a period in which the vessel slowly drifted with the current towards the northeast. During this period, the seismic vessel "Geo Pacific" (82 m length), was surveying to the northeast along an 85 km straight transect parallel to the coastline, using standard protocols for 3D seismic data acquisition, at a speed of about 1.6 m s^{-1}. The geographic position and time of the emission of the two air gun arrays (discharge about every 10 s) were recorded. The position of RV "Håkon Mosby" was about 2 km, (1.0 nmi) from the intended course line of seismic vessel "Geo Pacific," with a maximum distance between the vessels of 27 km at the start of the observations.

Sonar

Herring schools were continuously observed using a Simrad SH80 omnidirectional fisheries sonar (Figure 1). The schools were later verified to be composed of herring by pelagic trawling (Løkkeborg *et al.*, 2012). This multibeam sonar was operated using a 360° horizontal fan (64 beams) at 120 kHz, with a pulse repetition rate of 1 s^{-1}, recording to 400 m range. The horizontal sonar fan operated while tilted down 4°, targeting herring schools at depths of 0–50 m. Unprocessed data were stored for each ping from the sonar-control computer through an Ethernet link to a data-logging computer. The logged beam data contains a start ping telegram with sonar parameters, as well as a 16-bit amplitude data telegram (Simrad, 2011).

Sonar data were post-processed using the software "Processing system for omnidirectional fisheries sonar" (PROFOS), which is a module of the Large Scale Survey System (Korneliussen *et al.*, 2006, www.marec.no, Bergen, Norway). The sonar data were displayed as a circular image with the vessel at the centre and a diameter equal to the sonar operational range (i.e. 400 m). When a school was visually detected, a mouse click on top of the centre of each school ("to seed a school") told the software to automatically find the adjacent cells, where uncalibrated volume backscattering strength (S_v) ranged from − 10 to − 50 (dB re m^{-1}), and group them into one school ("growing a school"). This growing procedure was repeated for the ping where the school was seeded and for consecutive pings (i.e. 5 to 10 pings before and after the seed) until the school was no longer detected in the sonar. For each detected school, the geographic position, date, time, mean S_V, and school area (m^2) were computed. From successive detections of the same school, geo-referenced positions were smoothed using a cubic smoothing spline (smooth.spline, degree of smoothing set by cross validation, default parameters; R Development Core Team, 2010); the school's swimming speed and direction were computed from the fitted curve. School tracks with $<$ 3 contiguous detections were discarded.

Hydrophone buoy

At the start of the experiment, a 3-m tall drifting buoy, equipped with a Naxys Ethernet hydrophone at 8 m depth, was released from the vessel. The drifting buoy was designed to minimize heave movements caused by surface waves, and buoy drift from wind stress (Øvredal and Totland, 2012). The observed drift rate of the buoy was assumed to correspond to the predominant near-surface currents. Data on buoy movement, geographic position and hydrophone recordings were transmitted in real time by radio to the research vessel. The smoothed direction and speed estimates from the buoy's GPS output were calculated in the same fashion as the herring schools tracked with the sonar.

Analysis

An integrated analysis of the seismic, sonar and buoy data was conducted using UTC time as a reference. The position and time of each air gun emission from the seismic vessel was recorded, and the positions from the emissions and the schools were converted into a Cartesian coordinate system (R-language SoDA package, geoXY function; R Development Core Team, 2010). The conversion from geo-referenced positions to Cartesian coordinates used the central air gun emission position (69°7.39'N 36°9.49'W) as the reference point. For each tracked school, the position of the air gun emission, along with the mean centroid position of the school, was used to calculate the direction and range to the stimulus (Figure 2).

The observed geo-referenced velocities for each school i can be decomposed as:

$$u_i = u_m + u_{c,i} + u_{r,i}, \tag{1}$$

where $u_{c,i}$ is the passive drift current for school i, and the active swimming component is decomposed into a constant velocity component u_m, which can be interpreted as the mean migration component, and a response velocity $u_{r,i}$ that can track changes in school swimming behaviour over the course of the experiment. These changes may be attributed to either a response to the approaching seismic vessel or to unrelated changes in swimming velocity observed in the experiment. The objective is to detect changes in $u_{r,i}$, and examine whether these changes are associated with the approach of the air gun array. The relative magnitude between $u_{r,i}$ and u_m will also give an indication of the strength of the response compared with the fish behaviour prior to exposure.

The drift velocity of the hydrophone buoy was matched to the mean time of the school detection and was used as an estimate of the drift velocity $u_{c,i}$. The mean fish movement, which can be interpreted as the fish migration component, was estimated by taking the mean velocity of the schools with the water current estimate subtracted, i.e. $u_m = \overline{u_i - u_{c,i}}$. The response velocity $u_{r,i}$ was then found by rearranging Eq. (1).

Three response variables were defined: the directional response, the school speed and the school area. Assuming that the most likely response to the seismic vessel was directed (i.e. swimming away from the air guns), we defined the school's directional response to the seismic vessel as the component of the response velocity pointing away from the seismic vessel, i.e.

$$r_i = u_{r,i} \cdot e_i, \tag{2}$$

where e_i is a unit vector pointing from the air gun emission to the mean position of the school (positive is swimming away), and · is the dot product, i.e. the projection of the velocity onto the unit vector. The school response speed is given by

$$s_i = |u_{r,i}|, \tag{3}$$

where | | denotes the absolute value of the velocity. Note that this is only the relative change in speed, since it is based on the response velocity $u_{r,i}$, i.e after the current and the long-term mean velocity have been removed; see Eq.(1). Finally, a potential fright response could increase the packing density and thereby decrease the observed school area, A_i. These three variables were used to detect potential changes in school behaviour as the seismic vessel approached and passed.

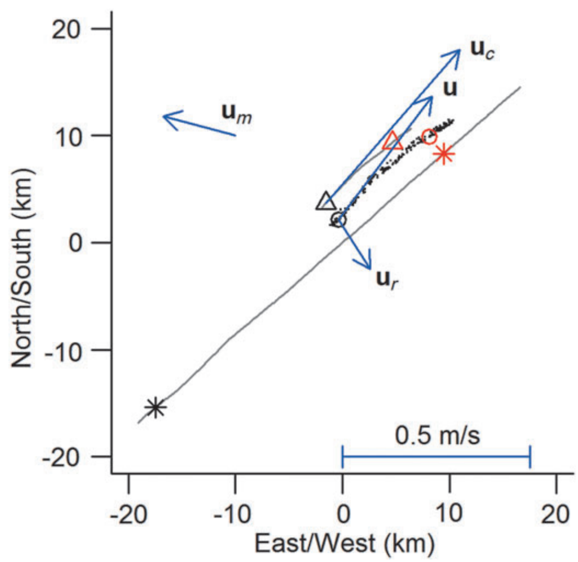

Figure 2. Overview of the experiment and definition of variables. The origin in the figure corresponds to the reference position (69°7.39′N 36°9.49′W) used to convert positions to Cartesian coordinates. The x-axis and y-axis are distances in km relative to east–west and north–south, respectively. The black dots are the positions of each school, and one example school, denoted with a black circle, serves as an example. The annotated blue arrows denote the various velocity components of the example school i. u is the observed georeferenced school velocity, u_c is the current velocity estimated from the drifting buoy, u_m is the mean response velocity across all schools (the placement is arbitrary since this velocity component is the same for all schools), and u_r is the response velocity of interest. The blue scale bar indicates the speed of the velocity components. The black and red symbols denote the position of the seismic vessel (asterisks), hydrophone buoy (triangles) and the seismic vessel (circles) at the time of the example track (black symbols), and the closest point of approach (red symbols). The grey lines associated with the asterisks and triangles are the track lines for the seismic vessel and the buoy, respectively.

Statistics

The null hypothesis is that the directional response, school speed and school area do not change as the seismic vessel approaches. Under the null hypothesis, one would expect no change in r_i, s_i or A_i as a function of time t relative to closest point of approach (CPA).

To test for an effect of the seismic vessel on herring behaviour, we fit a generalized additive model (GAM) to the data using a smoothing spline with time as the argument [gam(y ~ s(t))] (R mgcv package), where s() is a smoothing spline and y [alternatively log(y)] is one of the three response variables. The speed and school areas were $\log_{10}$ transformed to achieve normally distributed residuals as well as homoscedasticity. This was evaluated using the gam.check function implemented in R (supplementary material). Note that if the effect of the modelled curve was significant, it may not have been caused by the seismic vessel: to imply an effect, any detected responses needed to be attributed to the passage of the vessel. However, if the effect was not significant, this meant that the observations of herring school behaviour were constant over time and, consequently, no effect could be attributed to the approaching seismic vessel.

Results

The current velocity estimated from the buoy drift was relatively uniform during the experiment, with a moderate decrease in speed and a slight change to a more westerly direction as the experiment progressed (Figure 3). The mean buoy drift speed was 0.57 m s^{-1} (1.11 knots), and the drift direction varied between 38.4 and 62.2 degrees. The buoy drift data were converted to vectors in Cartesian coordinates and used as an estimate of u_c

The sound exposure level (SEL) from each air gun array, measured by the drifting buoy, increased from 125 to 155 dB re 1 μPa^2 s during the approach of the vessel (from about 27 to 2 km, Figure 4a). After a sharp increase during the first hour, the SEL remained at levels above 145 dB re 1 μPa^2 s, which was probably caused by the sound speed profile in the upper water column in the shelf break region (for details with respect to sound propagation in the area, see Hovem *et al.*, 2012).

A total of 241 schools were analysed, and a corresponding track was created from all detections of the same school, with a mean of 68 detections for each school track. With the sonar pulse repetition rate of 1 s^{-1}, this corresponds to about 1 minute. The mean school surface area was 264 m^2, corresponding to about 12 m school diameter, assuming a circular shape.

The constant velocity component, u_m indicates a mean swimming speed of 0.35 m s^{-1} (1.3 body length s^{-1}) with a direction opposite to that of the drift current, c.f. Figure 2. On average, the fish were swimming against the current at approximately half the current speed.

The mean response velocity u_r is the residual velocity after subtracting the mean swimming velocity and the current velocity. A randomly chosen school and the corresponding response velocity area shown in relation to the other velocities in Figure 2. The mean response velocity was zero by definition, but the mean response speed was 0.22 m s^{-1}, calculated as $\frac{1}{N}\sum_i |\mathbf{u}_{i,r}|$ where N is the number of schools and || indicates the absolute value of the velocity (speed). The magnitude of the mean response speed was smaller than $|u_m|$, (the mean velocity attributed to fish migration), which gives some indication that the herring did not exhibit large changes in swimming velocity away from the seismic air guns.

There was no evident relationship between the sound exposure level or distance of the seismic array and the speed (s_i, Figure 4b),

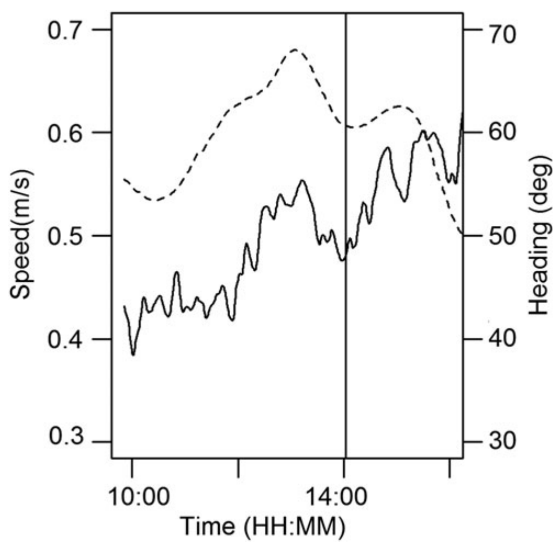

Figure 3. The speed (dotted line) and direction (solid line) of the drifting buoy that is used to estimate u_c. The time is linked to the mean time each school was observed.

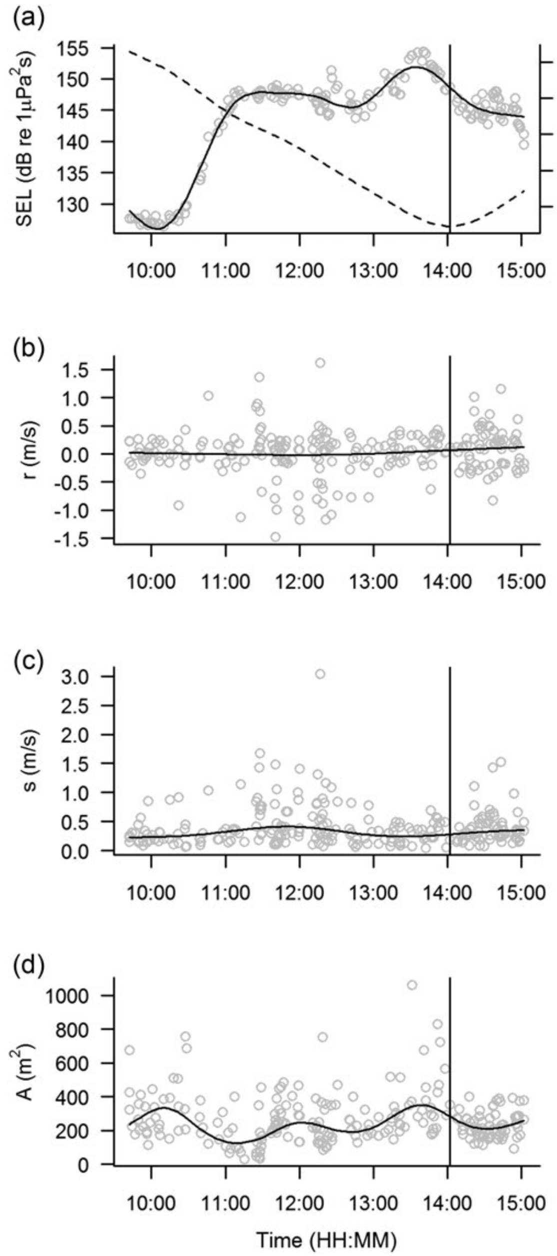

Figure 4. (**a**) The sound exposure level (SEL, solid line) for each air gun transmission observed at the drifting buoy, and the distance between the acoustic source and the buoy (dotted line). A smoothing spline is fitted to the observations. The black vertical line is the time of closest point of approach (CPA). The peak in SEL is observed before CPA since the position of the buoy was not the same as the position of the closest school (c.f. Figure 1). (**b**) The solid line is a fitted smoothing spline to the response r_i for each school (grey circles). The "signal" seen in these responses stems from the research vessel changing its position relative to the seismic vessel and the fact that the current u_c remains fairly constant (c.f. Figure 2) and that the mean fish behaviour u_m is substantially larger (c.f. Figure 1) than the speed of the response velocity component u_r. (**c**, **d**) Similar to (**b**), but with speed and school area as explanatory variables.

directional response (r_i, Figure 4c), or the area of herring schools observed with the sonar (A_i, Figure 4d). When splines were fitted to these responses (R, GAM), there was no significant effect for r_i ($p = 0.24$). There was a moderate effect for [$\log(s_i)$] ($p = 0.002$), with an ~0.2 m s^{-1} increase that may have been related to the increase in SEL observed after 11:00 UTC, but this did not coincide with the CPA. A stronger significant effect was found for school area [$\log(A_i)$] ($p < 0.001$), however, it did not coincide with either SEL or the time of the CPA. These results reinforce the notion that the mean swimming behaviour persistent throughout the experiment was stronger and more important than the effect of the residual swimming caused by a local response, i.e. a potential response to the approaching seismic vessel.

Discussion

Limited research has been conducted on the effects of seismic air gun surveys on the behaviour of pelagic schooling fish at spatial and temporal scales relevant to behavioural reactions (i.e. metres and seconds). The use of omnidirectional fisheries sonar represents a new method for tracking the behaviour of individual schools. The technique is well suited to detecting changes in behaviour caused by an approaching seismic vessel, and similar techniques have been used to investigate the behavioural response of herring to low and mid-frequency naval sonars (Doksæter *et al.*, 2012). As suggested by Godø *et al.* (2004), we used a drifting vessel (drift speed 0.6 m s^{-1}) as a sonar platform, as opposed to a vessel operating at standard survey speed (5.1 m s^{-1}). Consequently, the duration for which each school was tracked increased, leading to improved accuracy in the estimates of school swimming speed and direction.

The two main currents that dominate the study area are the Norwegian Coastal current and the Norwegian Atlantic current, which flow on and off the continental shelf, respectively. Poulain *et al.* (1996) indicate that in the confluent region the sustained current speed averages 0.6 m s^{-1} with an upper limit of 1.1 m s^{-1} and a mean current direction approximately aligned with the mean along-slope direction (i.e. northeast). Estimates of a fine-scale numerical ocean modelling system (Røed and Kristensen, 2011) for the same time and region of our study, predict a current speed of 0.6–1 m s^{-1} in the northeast direction. This provides a large-scale overview of the surface current system in the area, and is consistent with the drifting buoy observations used as a current estimate in our study.

During summer, when our experiment was performed, young herring aggregate in small and shallow schools in an active feeding migration in the current system along the coast of Vesterålen (Dragesund *et al.*, 2008). This leads to a northerly transport towards the Barents Sea. Løkkeborg *et al.* (2012) report high zooplankton abundance in the region during the study, with aggregations consisting mainly of copepods of densities higher than 200 g m^{-2}. Copepods were also the main item in the full stomachs found when sampling herring in the area (average total length 27.7 cm, Løkkeborg *et al.*, 2012). Our results showed that herring schools exhibit net displacement with the prevailing current, but that they actively swim against the current at a relatively low speed. It is likely that this is a strategy for increasing their prey encounter rate as a sit-and-wait predator strategy, similar to a fish in an aquarium swimming slowly against the current to increase feeding efficiency (Metcalfe *et al.*, 1997).

If the disturbance is perceived as a potential predator (Frid and Dill, 2002), we may interpret the lack of a strong reaction to the air gun survey as a trade-off between the cost of lost feeding opportunity and the assessed risk of predation (Ydenberg and Dill, 1986; Lima and Dill, 1990). If we compare the mean swimming velocity (u_m) with the response velocities (u_r), we see that the mean swimming dominates. This shows that the fish largely continue their existing behaviours instead of responding to the approaching air gun array. This is in agreement with previous studies of herring, in which reduced responses to acoustic stimuli while feeding (Fernandes *et al.*, 2000; Doksæter *et al.*, 2012) and stronger responses while overwintering (Vabø *et al.*, 2002; Hjellvik *et al.*, 2008) have been observed. However, it is important to recognize that our observations were conducted during a window of opportunity inside a larger survey (Løkkeborg *et al.*, 2012), which allowed for observation during a single seismic shooting line, but no time for replicates or control sampling. Therefore, one should be cautious when generalizing from the present results.

The air gun signals may potentially be detected by fish at long range (i.e. 33 km; Engås *et al.*, 1996), but the cost of a consistent response to the stimulus would be high. If the fish can detect the approximate range to the disturbance, as has been demonstrated for cod (Schuijf and Hawkins, 1983), the risk could be assessed by distance rather than SEL or its equivalent. This also relates to signal habituation. When the fish are repeatedly exposed to a stimulus, the perception of risk may change and lead to weaker responses. In Olsen (1976) herring habituation was observed when the air gun sound stimulus was repeated at time intervals less than several minutes, and clear signs of habituation were observed 120 s after exposure to an air gun (Dalen, 1973). The habituation time in these two investigations was of the order of minutes, while the seismic shooting in the present work lasted for about 6 h. In tank experiments, another clupeid (*Alosa sapidissima*) also responded only for a few seconds, and returned to normal swimming behaviour after repeated ultrasonic stimuli (Plachta and Popper, 2003). In this context, the repeated exposures to the seismic emissions may have led to a modified risk assessment and consequently to a weaker response or even a lack of response.

We have demonstrated a lack of response to an approaching seismic vessel for feeding herring off the coast of Vesterålen, and attribute the unanticipated lack of response to the strong motivation for feeding combined with the slow approach of a distant stimulus. We cannot, based on this work, conclude that no other effects of noise exposure were present: for example, we have not directly measured feeding success. However, given that no major changes in behaviour were observed, we assume any effects were relatively modest in nature.

Supplementary data

Supplementary material is available at the *ICES Journal of Marine Science* online version of the paper, and consists of diagnostic information about the fitting procedure and results of fitted GAM models.

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