Silent ships do not always encounter more fish (revisited): comparison of acoustic backscatter from walleye pollock recorded by a noise-reduced and a conventional research vessel in the eastern Bering Sea

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Vessel-induced avoidance behaviour is potentially a major source of error in surveys of fish populations. Noise-reduced research vessels have been constructed in an effort to minimize fish reactions to auditory stimuli produced by survey vessels. Here, measurements of acoustic backscatter from walleye pollock (*Theragra chalcogramma*) made on the eastern Bering Sea Shelf from the conventional NOAA ship "Miller Freeman" (MF) are compared with similar measurements made on the noise-reduced NOAA ship "Oscar Dyson" (OD). As in a previous study, acoustic abundance measurements from these vessels were equivalent during daylight, when large-scale acoustic surveying is conducted. However, significant differences were observed at night: on average, 44% more pollock backscatter was observed from OD than MF. Observations with a free-drifting echosounder buoy suggest that the night-time discrepancy is attributable to a stronger behavioural response to the passage of the louder MF, and a resulting decrease in pollock target strength. Pollock did not exhibit a strong reaction to the passage of OD. These observations are consistent with previous comparisons of these vessels, which show that with vessel differences, the noise-reduced OD detects more pollock.

Keywords: acoustics, noise-reduced vessel, vessel avoidance response, walleye pollock.

Introduction

Fish dive or move laterally from approaching vessels in a manner consistent with an avoidance reaction (Olsen, 1990; Fréon and Misund, 1999; Ona et al., 2007). Although it is unclear how widespread these reactions are, vessel-induced changes in behaviour are of concern because they have the potential to introduce biases into the acoustic estimation of fish abundance, primarily by changing the availability of fish to the acoustic beam or altering the orientation of the fish and hence their acoustic-backscattering strength (Olsen, 1990; Soria et al., 1996; Vabø et al., 2002; Løland et al., 2007). Vessels produce loud sounds in the frequency range of fish hearing (Mitson, 1995), and fish react to vessels at distances of several hundreds of metres (Misund et al., 1996; Handegard and Tjøstheim, 2005; De Robertis and Wilson, 2010), both of which suggest that underwater sound, which incurs low propagation loss compared with other potential stimuli, is the primary stimulus for the reactions. In response to these concerns, proposals for maximum underwater radiated noise levels (expressed as sound pressure measured in the far field) for research vessels (Mitson, 1995) were formulated under the auspices of ICES. The proposals for research vessel-radiated noise include limits for noise emission in the hearing range of fish (<1 kHz) aimed at reducing fish-avoidance responses, and higher-frequency (>1 kHz) limits aimed at maximizing the performance of acoustic instruments. The lower-frequency limits were based on the hearing capabilities of fish with sensitive hearing (Atlantic cod, *Gadus morhua*, and Atlantic herring, *Clupea harengus*) and the assumption that behavioural reactions will be initiated when fish are exposed to sound pressure 30 dB above their hearing threshold.

Several research vessels have been built to comply with the ICES proposals for underwater radiated noise. These noise-reduced ships produce substantially less radiated noise than conventional, i.e. not noise-reduced, research vessels (Mitson and Knudsen, 2003). Given that low-frequency noise reduction is an attempt to reduce fish avoidance, it is reasonable to question whether acoustic estimates of abundance from noise-reduced vessels are comparable with those made with conventional vessels. The answer can have important consequences for fisheries management, because a bias can be introduced into abundance time-series if fish behaviour or the vessel used to generate an abundance time-series changes. Despite these concerns, the impact of noise reduction of research vessels on the behavioural reactions of fish, and the consequences for acoustic estimates of fish abundance, remains poorly characterized (Ona et al., 2007; Sand et al., 2008; De Robertis et al., 2010).

Direct comparisons of acoustic estimates of fish abundance from just two pairs of noise-reduced and conventional research vessels have been reported to date. The first study, which compared the noise-reduced "G. O. Sars" with the smaller, but louder, conventional "Johan Hjort" (Ona *et al.*, 2007), produced an unexpected result: Atlantic herring exhibited a stronger diving response to the noise-reduced vessel, with much of the reaction taking place after vessel passage. De Robertis *et al.* (2008, 2010) compared acoustic measurements of walleye pollock (*Theragra chalcogramma*) from the conventional NOAA ship "Miller Freeman" (MF) and the noise-reduced NOAA ship "Oscar Dyson" (OD). Equivalent backscatter was observed from the vessels during summer in the eastern Bering Sea (De Robertis *et al.*, 2008), which indicates no major differences in avoidance reaction that influence acoustic abundance estimates in that case. In contrast, consistently higher backscatter was observed from OD than from MF in two winter comparisons in the Gulf of Alaska (Shelikof Strait and the Shumagin Islands), suggesting a different reaction to the vessels there (De Robertis *et al.*, 2010). Observations with a buoy-mounted echosounder in the Shumagin Islands confirmed that the difference in backscatter was attributable to reduced reactions to the noise-reduced vessel (De Robertis and Wilson, 2010). The pollock in those locations were distributed deeper (and farther from the survey vessel) than those during summer in the eastern Bering Sea. No vessel differences were observed in winter in the Bogoslof area of the Bering Sea, where the pollock were distributed even deeper (400–700 m).

At a given location, the MF and OD vessel differences were depth-dependent, i.e. a stronger reaction was observed for the shallowest fish, as one might expect if the reaction is caused by vessel noise, which is highest near the vessel. However, this depth effect was not consistent among locations: for example, equivalent backscatter was observed by the two vessels in the eastern Bering Sea where the fish were shallower than in other areas in the Gulf of Alaska where there was a vessel difference. The lack of a simple depth-dependent pattern in the comparisons of fish reactions across comparisons of a single pair of conventional

and noise-reduced vessels demonstrates that fish reactions cannot be predicted solely based on hearing physiology and vessel-radiated noise as assumed in the ICES proposal, and that other, less well-understood factors, such as environmental conditions, season, fish physiological state, and background noise, are likely to influence how fish react to vessels.

There is a substantial fishery for walleye pollock, primarily in the eastern Bering Sea (Bailey *et al.*, 1999). A long time-series of acoustic surveys is used in the stock assessment (Karp and Walters, 1994). The surveys were conducted primarily by MF, and OD has continued the time-series since 2007. Given the observations of pollock reactions to these vessels in other areas and the magnitude of the potential bias introduced by vessel-dependent avoidance behaviour, we repeated the comparison of acoustic estimates of pollock abundance from the conventional MF and noise-reduced OD in the eastern Bering Sea to confirm our previous study in the area (De Robertis *et al.*, 2008). We also used an instrumented buoy (Godø and Totland, 1996) to observe the reactions of pollock to the approach of the two vessels directly. The goals of the work were to (i) verify the result of De Robertis *et al.* (2008) that acoustic estimates of pollock from OD and MF during summer in the eastern Bering Sea are equivalent, (ii) characterize the behavioural response of pollock when approached by the vessels, and (iii) consider the observations in the context of previous comparisons of these vessels.

Methods
Study design
Acoustic backscatter recorded aboard the National Oceanic and Atmospheric Administration (NOAA) ships "Oscar Dyson" and "Miller Freeman" was compared during an experiment conducted from 26 to 29 July 2008 in the eastern Bering Sea, using the same methods as those in a previous study conducted in 2006. The methods are described in detail in De Robertis *et al.* (2008) and are therefore only covered briefly here. The experiment was conducted in the same area as the 2006 experiment (Figure 1a),
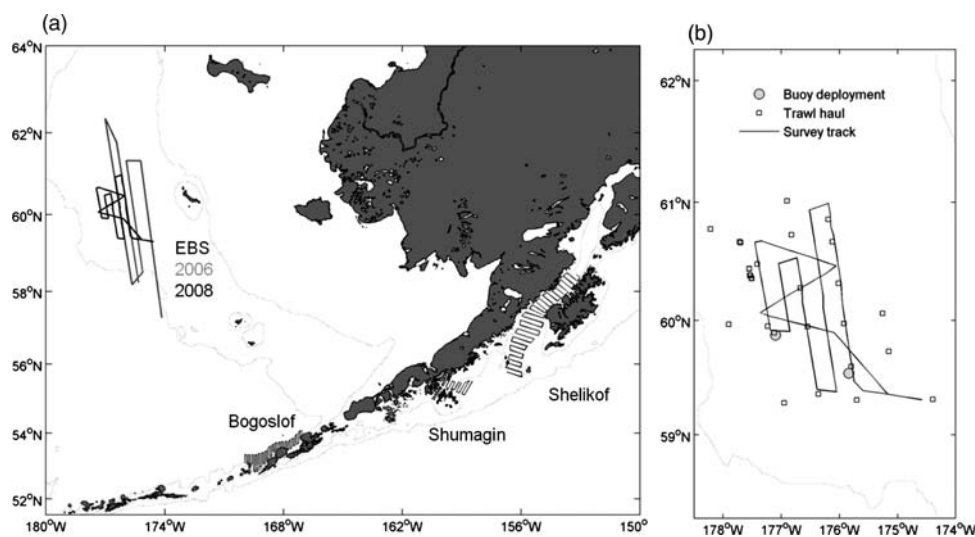

Figure 1. Maps of the study site. (a) Location of experiments comparing the OD and the MF in the eastern Bering Sea (EBS), the Bogoslof Island area, the Shumagin Islands, and Shelikof Strait. (b) Details of the 2008 experiment in the eastern Bering Sea, showing the side-by-side trackline and the location of nearby trawls conducted during the echo-integration trawl survey preceding the experiment. The location of buoy experiments and trawls conducted at each buoy deployment site are also shown. The grey dotted lines demarcate 70 and 500 m depth.

immediately after the OD completed the 2008 pollock abundance survey.

The research vessels are of similar size, but OD was built to conform to the ICES proposals for radiated noise and therefore produces substantially less radiated noise in the hearing range of fish than the MF (see De Robertis et al., 2008, for detail). The vessel comparison consisted of acoustic measurements in which the vessels travelled side by side on transects offset laterally by 0.5 nautical miles (miles hereafter). The 0.5-mile vessel separation distance was selected so that noise from MF, the louder vessel, was not expected to dominate the radiated noise perceived by fish near OD (De Robertis et al., 2008). The vessels switched sides, i.e. the vessels alternated which was on the port side, at least every 50 miles. Measurements were conducted by both day and night. Bottom depths in the study area averaged 134.1 m and ranged from 126.3 to 151.7 m. The weather was mild, with average wind-speeds of 6.2 m s^{-1} (range 1.1–9.6 m s^{-1}), with wave heights of <2 m. Vessel speed averaged 12.1 knots (range 11.3–12.7 knots).

At two sites, a free-drifting buoy equipped with a 38-kHz echo-sounder (described in De Robertis and Wilson, 2010) was used to observe the reactions of pollock as the vessels approached (Figure 1b). The first deployment was conducted on 23 July before the arrival of MF. In the second deployment, conducted on 28 July, OD and MF took turns passing the buoy at intervals of 15 min. These buoy observations require a homogenous distribution of fish (De Robertis and Wilson, 2010), so the deployments were conducted during the night when pollock form more evenly distributed layers, as opposed to their patchy daylight schools.

Acoustic backscatter thought to be pollock was verified by targeted fishing with a midwater Aleutian wing trawl equipped with a 1.3-cm mesh liner in the codend (Honkalehto et al., 2002). One haul was conducted after each buoy deployment, and another 26 hauls were conducted within 25 miles of the trackline used for vessel comparison (Figure 1b) during the abundance survey conducted before the experiment (6–22 July). The catch was dominated by walleye pollock, averaging 98 ± 3% (±s.d.) of the trawl catch by weight. The pollock differed in size from the 2006 experiment, with a greater abundance of pollock aged 2 (~25 cm) and 3 (~32 cm) in 2008 (Figure 2).

Vessel data collection and processing

Backscatter strength was recorded along the vessel tracks at 18, 38, and 120 kHz using Simrad EK60 echosounders (note that
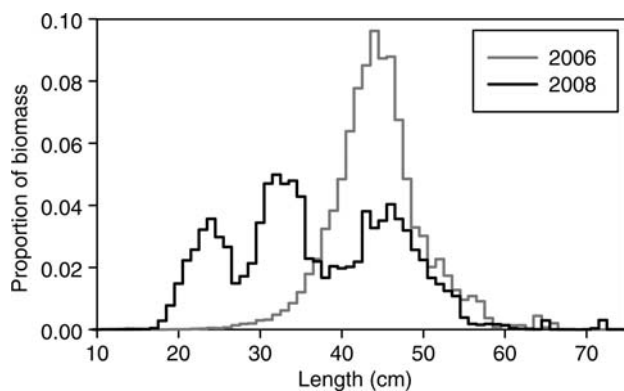

Figure 2. The size distribution of pollock observed in the acoustic surveys conducted near the 2006 and 2008 vessel-comparison experiments in the eastern Bering Sea.
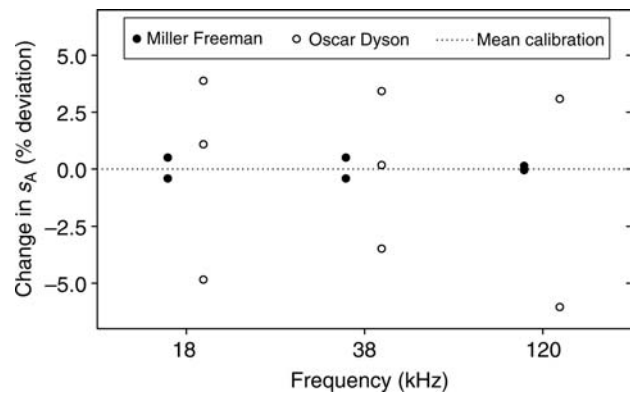

Figure 3. Precision of on-axis calibrations and their implications for backscatter measurement. Each point represents the effect of using a single on-axis sphere calibration for s_A measurements compared with applying the mean integration gain from all calibrations combined (as has been done in this study). Results are expressed as percentage deviation = $(2(\text{Gain} - \overline{\text{Gain}})/\overline{\text{Gain}}) \times 100$, where Gain corresponds to the integration gain in linear units. This calculation accounts for the two-way effects of integration gain on backscatter measurements. For the OD 120 kHz, only two symbols are visible, because two symbols overlap.

reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA) equipped with transducers of the same model and operated with equivalent settings (see De Robertis et al., 2008, for detail). The echosounder on-axis sensitivity was calibrated using the standard sphere method (Foote et al., 1987), three times (2 June, 11 July, 31 July) for OD and twice (25 and 31 July) for MF. The average gain resulting from these calibrations was used in subsequent data analyses. These repeat calibrations (Figure 3) provide a measure of the uncertainty attributable to calibration: if we had chosen to apply any of the individual calibrations instead of the mean value, we would expect a deviation of up to 5% in measured s_A, depending on the frequency. Calibration precision at 38 kHz, which is the primary frequency used to estimate pollock backscatter, was within 3% of the mean value used in this study.

Backscatter was allocated to two classes representing a near-surface layer of unknown composition, and a deeper layer of walleye pollock (cf. De Robertis et al., 2008; their Figure 3). Backscatter from walleye pollock was restricted to ≥3 m above the seabed so that the results would conform to the data used for stock-assessment purposes (Wespestad and Megrey, 1990). An S_v integration threshold of −70 dB re 1 m^{-1} was applied at 18 and 38 kHz, and a −60 dB re 1 m^{-1} threshold was used at 120 kHz, to suppress low intensity but persistent backscatter from zooplankton. The nautical-area scattering coefficient (s_A, m^2 nautical mile^{-2}, defined in MacLennan et al., 2002) was averaged 0.1 mile along-track and 1 m deep.

Statistical analysis of echosounder data

Acoustic measurements were averaged into 5-mile elementary distance sampling units (EDSUs). To minimize variability, only those EDSUs in which both vessels observed an average s_A of >20 m^2 mile^{-2} at the frequency in question, and those where the mean bottom depth observed by both vessels differed by <2%, were used in further analyses. This resulted in a frequency-dependent sample size, with 103/99/102 suitable EDSUs for

pollock at 18/38/120 kHz, respectively. Scattering from the near-surface layer was strongly frequency-dependent, and 91/70/29 EDSUs passed these criteria at 18/38/120 kHz, respectively.

We applied the method of Kieser *et al.* (1987) to estimate the ratio of pollock backscatter observed by OD and MF. The echo-integration measurements were modelled as

$$s_{A,i,j} = \alpha_j \rho_i \varepsilon_{i,j}, \quad i = 1, \ldots, n, \ j = \text{OD, MF}, \quad (1)$$

where $s_{A,i,j}$ is the nautical-area scattering coefficient recorded at EDSU i by vessel j, ρ_i the fish areal density at EDSU i, α_j a vessel-specific scaling factor, and $\varepsilon_{i,j}$ the lognormally distributed random noise. The vessel ratio $R = \alpha_{\text{OD}}/\alpha_{\text{MF}}$ is defined as the ratio of the biases produced by the vessels and can be used to scale backscatter measurements between vessels (i.e. $s_{A,\text{OD}} = s_{A,\text{MF}}R$). R can be derived from the difference in observed backscatter:

$$d_i = \ln(s_{A,i,\text{OD}}) - \ln(s_{A,i,\text{MF}}) = \ln(\alpha_{\text{OD}}) - \ln(\alpha_{\text{MF}}) + e_i, \quad (2)$$

where $e_i = \ln(\varepsilon_{i,\text{OD}}) - \ln(\varepsilon_{i,\text{MF}})$ is normally distributed random noise, and

$$R = \exp(\bar{d}), \quad (3)$$

where $\bar{d} = n^{-1} \sum_{i=1}^{n} d_i$ is an unbiased estimate of R. Assuming no autocorrelation in d_i, the 95% confidence interval (*CI*) for R is $\exp(\bar{d} \pm t_{n-1,0.025} s_d n^{-0.5})$, where $t_{n-1,0.025}$ is the 2.5% quantile of the t-distribution with $n - 1$ degrees of freedom, and s_d is the standard deviation of d_i. The first lag autocorrelation of d_i was 0.11 ($p > 0.05$), which indicates that the assumption of no autocorrelation in d_i is largely met.

We computed a series of statistics to characterize the depth distribution of pollock observed with each vessel. The mean weighted depth (mwd) of pollock for each EDSU was calculated as

$$\text{mwd} = \frac{\sum_D D s_{A,D}}{\sum_D s_{A,D}}, \quad (4)$$

where D is depth (m) and $s_{A,D}$ is the s_A in the depth interval from $D - 1$ to D. In addition, the $p\%$ depth quantiles q_p ($p = 10, 20, \ldots, 90$) of the pollock vertical distribution were calculated by linear interpolation between D^+ and $D^+ - 1$, where D^+ is the shallowest depth, such that

$$\sum_{D=16}^{D+} s_{A,D} > 0.01p \sum_{D=16}^{D_{\max}} s_{A,D}. \quad (5)$$

The q_p depth quantile is therefore the minimum depth above which $p\%$ of the pollock were found in a particular EDSU. Vessel differences in pollock depth distribution were expressed as $\text{mwd}_{\text{OD}} - \text{mwd}_{\text{MF}}$, for mwd or $q_{p,\text{OD}} - q_{p,\text{MF}}$ for quantiles of the depth distribution.

Buoy observations

On two occasions, we used an instrumented buoy to observe the reactions of pollock as the vessels approached and passed the buoy directly. The buoy (described in De Robertis and Wilson, 2010) contains a Simrad EK60 38 kHz echosounder, with a transducer suspended 22.5 m below the surface. The shipboard 38 kHz echosounders were turned off to avoid interference with the buoy

echosounder. After the buoy was deployed and drifting over an aggregation of pollock, the vessels approached the buoy from 1 mile away, passed within ~5 m of the buoy, and continued along this track for 1 mile. Both deployments were conducted during darkness, when the pollock were more evenly distributed. OD conducted a trawl targeting the pollock aggregation at each site. Pollock accounted for >99.8% by weight and numbers in the catch at both locations. Pollock aged 2 dominated the catch, with a mean length of 25.5 cm at the first deployment site and 24.5 cm at the second.

The first deployment was before the arrival of MF at the study site, and OD made 14 runs at the buoy. During the second deployment, OD and MF took turns making runs at the buoy, each making seven passes. For each passage of the buoy, each vessel conducted a rectangular track which included one transect 2 miles long at the latitude of the buoy, and another one 1 mile north of the buoy. This pattern allowed the extraction of 14 × 2-mile transects in which the observations from the vessel echosounders could be compared (see De Robertis and Wilson, 2010, for detail). Vessel speeds averaged ($\pm$s.d.) 11.7 $\pm$ 0.2 knots during the first deployment, and 11.6 $\pm$ 0.3 knots during the second. During both experiments, a vessel passed the buoy every 15–20 min.

Analysis of the acoustic data from the buoy followed the methodology described in De Robertis and Wilson (2010). Observations at the time of the vessel's closest point of approach (CPA) to the buoy were compared with those during a reference period before CPA when the pollock were likely undisturbed. The time-series of s_A from the buoy echosounder was smoothed with an 11-s running mean to reduce temporal variability. Following previous studies (e.g. Vabø *et al.*, 2002; De Robertis and Wilson, 2010), observations during passage were taken as CPA $\pm$ 3 s, and the reference period was taken as 158–88 s before the CPA.

To describe the change in backscatter associated with vessel passage, the vessel-avoidance coefficient (va_{s_A}; cf. Vabø *et al.*, 2002) for each vessel pass i was computed as

$$\text{va}_{s_A,i} = \frac{s_{A,\text{pass},i}}{s_{A,\text{ref},i}}, \quad (6)$$

where $s_{A,\text{pass},i}$ is the s_A observed during vessel pass i, and $s_{A,\text{ref},i}$ is the s_A observed during reference period i. The results were summarized by computing the mean and 95% *CI*s over all passes on natural log-transformed ratios, then back-transforming these quantities.

We also tested for changes in pollock depth distribution associated with vessel passage. The mean weighted pollock depth (mwd) for each reference period and vessel passage was calculated following Equation (3). The difference between the mwd at passage and the reference period was computed as follows:

$$\text{va}_{\text{mwd},i} = \text{mwd}_{\text{ref},i} - \text{mwd}_{\text{pass},i}. \quad (7)$$

The change in depth was summarized by computing the mean and 95% *CI*s of va_{mwd} over all approaches.

Vessel observations during buoy observations

Vessel echosounder observations from the second buoy deployment were compared, to test whether differences in pollock backscatter during the experiment were observable. Observations on the 14 transects were compared pairwise to test for vessel differences in

acoustic observations (cf. De Robertis and Wilson, 2010), estimating the vessel ratio R [Equation (3)] and the vessel difference in pollock mwd (i.e. $\text{mwd}_{OD} - \text{mwd}_{MF}$) for each vessel pass.

Conditions during that period were favourable for an analysis of the target strength (TS) of individual fish. For each transect, the median backscattering cross section, median σ_{bs}, for single targets observed with a minimum target strength of -70 dB was computed for all single targets deeper than 35 m (σ_{bs} is a linear measure of TS; MacLennan *et al.*, 2002). Single targets shallower than 35 m were excluded, to remove the influence of targets in the near-surface layer that were unlikely to be from pollock. Single-target echoes were identified by the single-target detector of the EK60 (a modification of Ona, 1999), with the same (default) parameters used aboard both vessels.

Results
Vessel ratio
The vessel ratio, R, for pollock revealed a strong diel effect, with significantly higher mean values of R by night than by day (Figure 4a; *t*-test, $p < 0.005$ at all frequencies). By day, the *CI*s for R included 1.0 at all frequencies, but at night, R values were much higher (range 1.24–1.44, depending on frequency), with 95% *CI*s that did not include 1.0. For example, at 38 kHz, the primary frequency used in pollock surveys, the mean value of R for pollock at night was 1.44, which means that OD detected an average of 44% more pollock backscatter than MF at night. In contrast to pollock, the value of R for the near-surface scattering layer was equivalent by day and night (*t*-test, $p > 0.30$ at all frequencies). The value of R for the surface layer varied by frequency (Figure 4b), with 95% *CI*s that just excluded 1.0 at 18 and 38 kHz (the lower bound of 95% *CI* in both cases was 1.00).

The R-value for individual depth strata was consistently higher by night than by day (compare the results for the same depths in Figure 5a and b). By day, the value of R for individual strata was close to 1.0, with just one stratum having *CI*s that excluded 1.0. In contrast, the R-value at night was strongly depth-dependent, with values higher in shallower strata. For pollock between 60 and 80 m deep, OD detected an average of >2 times more
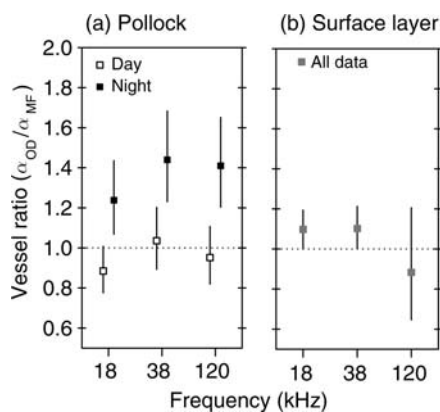

Figure 4. Vessel echosounder backscatter ratio (OD/MF) with 95% *CI*s for the side-by-side transects: (a) pollock backscatter and (b) near-surface backscatter. Results by day and by night are shown separately for pollock because there is a significant difference in the ratios. Estimates where the lower *CI* exceeds 1.0 demonstrate that the OD detects significantly more pollock backscatter than the MF.

pollock backscatter than MF, and the mean value tended to decease with depth (Figure 5b). At night, significant differences persisted over all strata up to the maximum observation depth of 140 m (i.e. the 95% *CI* consistently excluded 1.0). Pollock were distributed shallower by night (mwd 106.7 m; Figure 5) than by day (mwd 116.0 m; Figure 5).

Vertical distribution
There was no vessel difference in the vertical distribution of pollock backscatter by day or night (Figure 6; *t*-test, $p > 0.05$ in both cases). Although not significantly different, the pollock detected by OD tended to be skewed shallower (i.e. negative values in Figure 6), particularly at night. The depth of the seafloor in our observations was consistently $\sim$0.5 m deeper for OD than MF (as previously observed in measurements on randomized transects by De Robertis *et al.*, 2010). This difference may be due to inaccuracy in the assumed nominal vessel draft or differences in transducer pointing angles. This result indicates that the OD may slightly overestimate the range to a target compared with the MF, which would mean that the degree to which OD detects shallower pollock is $\sim$0.5 m greater than that shown. However, an adjustment of this magnitude would not change the inference of no significant difference in fish depth distribution observed by the vessels.

Buoy echosounder observations
OD passed the buoy 14 times during the first experiment, with little evidence of disturbing the fish layer either before or after vessel passage during the first buoy deployment (Figure 7a). The mean value of va_{s_A} was 0.99 with a 95% *CI* of 0.82–1.18 (Figure 8a). The mwd of pollock was also similar during the reference period and at vessel passage; va_{mwd} was -0.6 m (95% *CI* 1.7–0.5 m). The relatively small *CI*s in this experiment were likely attributable to the relatively uniform distribution of fish under the buoy.

OD and MF took turns passing the buoy during the second experiment. Visual inspection of the echograms gave the impression of little or no reaction to OD, but in some cases, there was potentially a response to MF (compare Figure 7b and c, which are 17 min apart). Overall, potential reactions to MF, i.e. a decrease in backscatter and a deepening of the pollock layer associated with passage, were observed in four of seven passes, and in none of the passes by OD, consistent with the mean values of va_{s_A} (Figure 8a). In addition, there was an indication of a deeper vertical distribution of pollock when they were approached by MF (Figure 8b), suggesting that the fish may have exhibited a stronger response to the passage of MF, with less and deeper pollock backscatter on average being detected by the buoy during MF passage than during the reference period. However, during that experiment, the changes in pollock backscatter between vessel passage and the reference period were highly variable. This is likely attributable to temporal changes in the mean backscatter observed as the buoy drifted over the patchy fish aggregations. The confidence intervals of va_{s_A} did not exclude 1.0, and va_{mwd} did not exclude zero for either vessel (Figure 8), indicating that the buoy observations of pollock backscatter strength and mean depth did not differ significantly between the reference period and the CPA for either vessel.
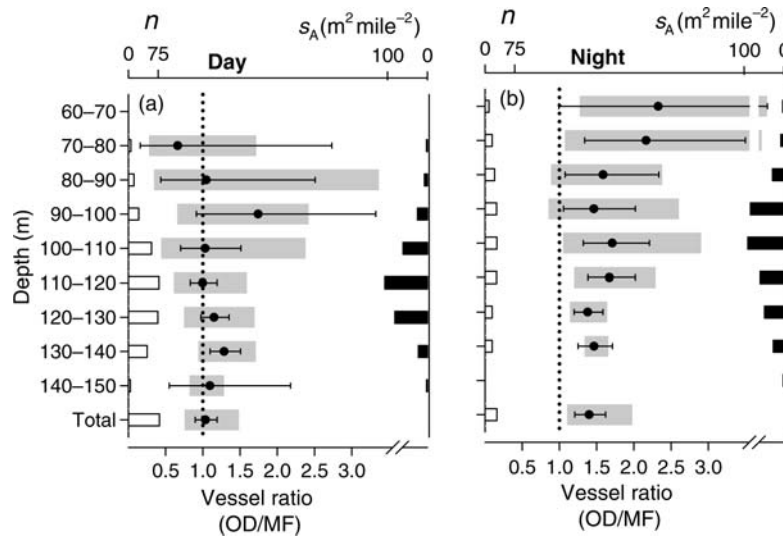
Figure 5. Vertically stratified 38-kHz vessel echosounder ratio (OD/MF) for (a) daylight and (b) night-time measurements. Each dot depicts the mean with 95% CIs, plus the first and third quartiles (the ends of the grey box). A vessel ratio of >1.0 indicates that the OD detected more pollock than the MF. The term total refers to the vessel ratio R averaged over the entire water column (cf. Figure 4). For each depth layer, only cases where the pollock s_A exceeded 20 m^2 $mile^{-2}$ in the EDSU and 1 m^2 $mile^{-2}$ in the 10-m depth layer for both vessels were included. The number of samples is indicated by the white bars on the left. The vertical distribution of s_A for all EDSUs used to compute the water column vessel ratio R is given on the right (black bars; results averaged over both vessels).
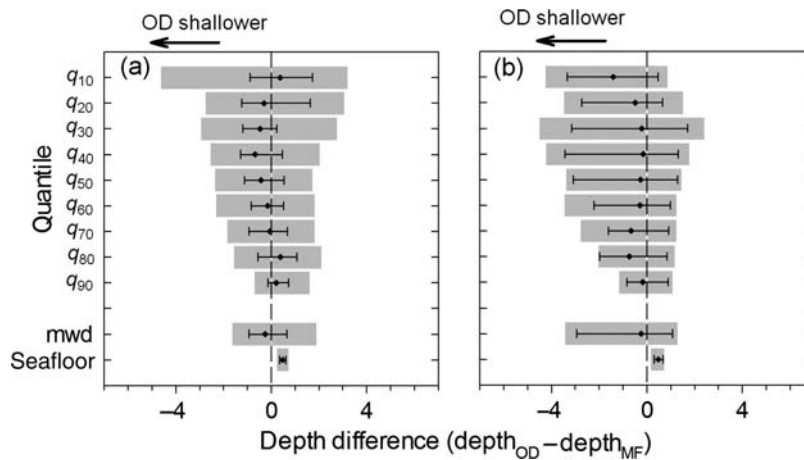

Figure 6. Boxplots of vessel differences in observed depth distribution. The quantile depth (i.e. the vessel difference in pollock depths for a given fraction of the population), the mwd of all observed pollock backscatter, and the depth of the seabed (seafloor) at 38 kHz are shown for (a) daylight and (b) night-time measurements. The depth difference is presented for the depth at which increasing proportions or quantiles of the population are found, starting from the surface. For a given 5-mile EDSU, the $q_{n\%}$ quantile is the shallowest depth above which $n\%$ of the total pollock s_A is encountered. The median with 95% CIs, plus the first and third quartiles (the ends of the grey box), is shown.

Vessel echosounder observations during buoy experiment

Observations from the vessel-mounted echosounders during the second buoy experiment were consistent with greater pollock reactions to MF than to OD. The latter detected significantly more pollock backscatter than the MF (paired t-test on $\ln(s_A)$, $p < 0.005$ for both frequencies). The average vessel ratio ($s_{A,OD}/s_{A,MF}$) was 1.31 at 18 kHz and 1.41 at 120 kHz (Figure 9a). The pollock mwd for OD and MF was similar (Figure 9b, paired t-test on mwd not significant for both frequencies). The median σ_{bs} for single targets detected deeper than 35 m was significantly higher for the OD than for the MF (paired t-test on transect median

σ_{bs}, $p < 0.01$ for both frequencies). Single targets were distributed throughout the water column, with mean target depths ranging from 52 to 82 m, and $\sim 90\%$ of single targets at depths shallower than 102 m. The median value of σ_{bs} was $1.9\times$ higher for targets detected by the OD at 18 kHz and $3.4\times$ higher for targets detected at 120 kHz (Figure 9c).

Discussion

The paired echosounder measurements indicate that walleye pollock respond differently to OD and MF by day and by night. During daylight, measurements of acoustic backscatter from the vessels were similar, supporting the conclusion of De Robertis
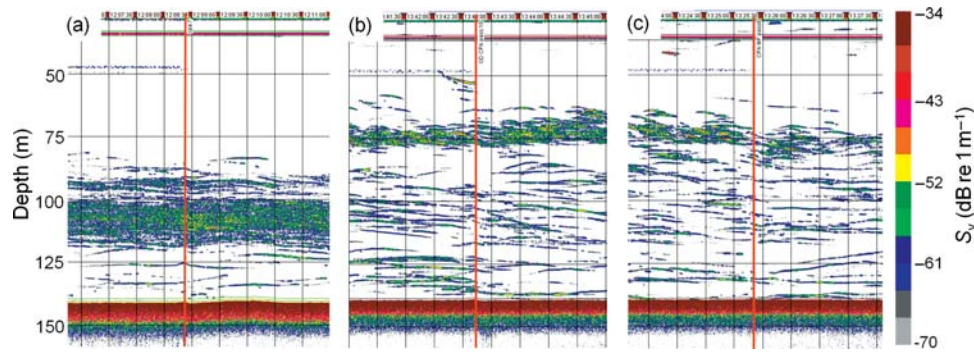
Figure 7. Echograms from the acoustic buoy during passage of (a) the OD during experiment 1, (b) the OD during experiment 2, and (c) the MF during experiment 2. The time at which the vessel passed closest to the buoy is shown by the orange line, and vertical lines demarcate intervals of 30 s. The backscatter visible as persistent horizontal marks <50 m (backscatter from a calibration sphere and a side lobe detecting the transducer rigging) was excluded from analysis.
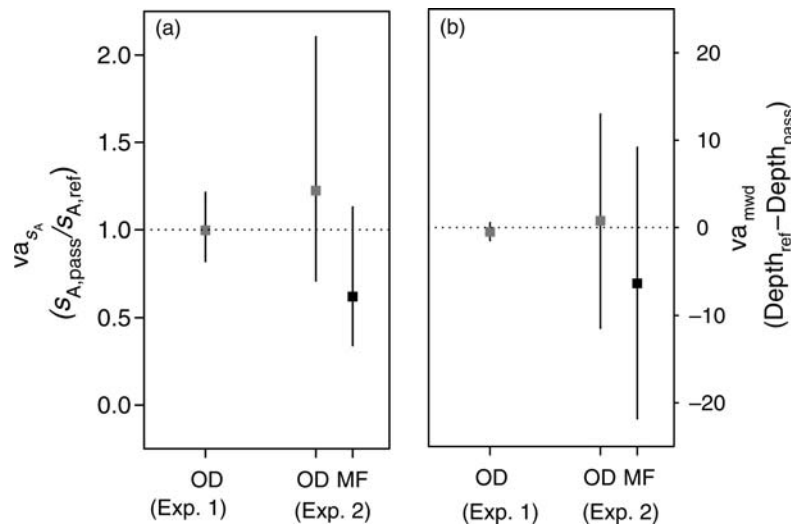

Figure 8. Acoustic buoy observations of changes in (a) acoustic backscatter strength (va_{s_A}), and (b) depth distribution (va_{mwd}) of walleye pollock between the reference period and the closest point of approach (CPA) of the vessel to the buoy. The mean and 95% CIs are shown.

et al. (2008) that daylight acoustic-trawl surveys for pollock in the eastern Bering Sea would produce similar results whichever of MF or OD was used to conduct the survey. In contrast, a substantial vessel discrepancy in pollock abundance was observed at night, with OD detecting an average of 44% more pollock backscatter than MF. We attribute these observations to differences in behaviour rather than to instrument performance, because a bias (e.g. in calibration) would not explain the diel difference or the smaller vessel ratio for the near-surface backscatter, which did not exhibit a diel difference. The depth distributions of pollock were apparently similar irrespective of vessel, with pollock distributed ~10 m deeper by day than by night. Although vessel reactions are often depth-dependent (Vabø *et al.*, 2002; De Robertis *et al.*, 2010), the shallower night-time distribution cannot be used to explain the higher value of R at night, because the depth-stratified values were close to 1 at all depths by day and >1 and decreasing with depth at night. The observed discrepancy between the day and the night value of R is therefore largely attributable to a diel difference in how the fish react to the vessels, rather than to a change in vertical distribution.

Taken together, the concurrent observations from the buoy and the vessels suggest that that pollock reacted differently to OD and to MF, but did not exhibit strong reactions to OD. During the first experiment, when OD passed the buoy, there was no evidence that OD caused a reduction in pollock backscatter or a diving response when it passed the buoy, as is often observed when fish react to approaching ships (Olsen, 1990; Vabø *et al.*, 2002; Ona *et al.*, 2007). High precision was observed among repeat passes. This is an important complement to the side-by-side measurements, because vessel comparisons allow for precise estimates of R by averaging over many pings, but do not allow for direct observation of behaviour, or absolute comparison of vessels (e.g. R cannot be used to distinguish between a case where there is notable avoidance of both vessels and little avoidance of both vessels).

During the second experiment, when OD and MF took turns passing the buoy, the results suggested an increased reaction to MF. In four of seven passes, MF seemingly disturbed the pollock under the buoy, causing a decrease in backscatter, but when OD passed, there was no obvious reaction. Although the observations from the buoy echosounder did not show a statistically significant
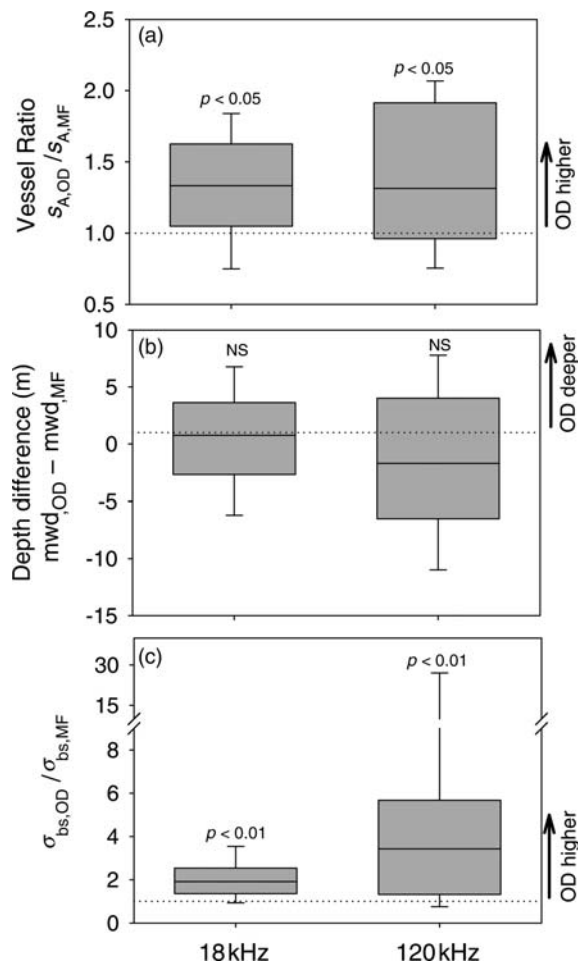
Figure 9. Comparison of acoustic measurements from the vessels during the second buoy experiment. (a) Ratio (R) of the mean pollock s_A observed by the OD and the MF. (b) Vessel difference in pollock mwd. (c) Ratio (OD/MF) of median backscattering cross section (σ_{bs}) for single targets detected shallower than 125 m. Results are shown for both 18 and 120 kHz echosounders. The horizontal lines within the boxes represent the median values, the lower and upper boundaries of the boxes demarcate the 25th and 75th percentiles, and the vertical lines the 10th and 90th percentiles of values observed in individual transects. The results of t-tests testing the null hypothesis of no vessel difference are given (see text for detail).

of TS detected by MF is likely attributable to a change in orientation as the pollock reacted to the vessel (Olsen, 1990; Barange and Hampton, 1994; De Robertis and Wilson, 2010).

In the 2006 vessel-comparison experiment in the eastern Bering Sea, a vessel-specific depth distribution of pollock was observed in a follow-the-leader configuration: MF observed pollock deeper when OD was in front (De Robertis *et al.*, 2008), whereas the depth distributions were not different when the vessels were side by side or when MF led. This result was inferred to be consistent with a diving response to the noise-reduced vessel, in which the reaction occurs primarily after the vessel had passed over the fish, as has been reported by Ona *et al.* (2007) for herring. Although we did not repeat the follow-the-leader transects in the recent experiment, the more direct echosounder buoy observations of pollock reactions in the eastern Bering Sea (this paper) and in the Shumagin Islands (De Robertis and Wilson, 2010) do not corroborate this inference. Rather, the buoy observations suggest that the responses to OD were negligible in an absolute sense and that when there were differences in reaction, pollock reacted more strongly to the passage of MF than to that of OD.

Comparisons of OD and MF have now been conducted in four areas where acoustic-trawl surveys are regularly conducted off Alaska, with the experiments in the eastern Bering Sea repeated in 2006 and 2008 (Figure 10). The daylight observations in the eastern Bering Sea reported here are consistent with the previous observations that the value of R in this area is ~ 1 during daylight (De Robertis *et al.*, 2008). A re-analysis of the limited night-time measurements (15 consecutive 5-mile EDSUs; see De Robertis *et al.*, 2008) from the 2006 experiment in the eastern Bering Sea indicates that there was also a diel difference then, with a vessel difference at night but not by day (Figure 10). In 2006, the OD detected an average of 24% more pollock backscatter than the MF, whereas the OD detected 44% more backscatter in 2008. This discrepancy in the 2006 and 2008 night-time vessel ratios may be related to the age distribution of pollock, because juvenile pollock were abundant in 2008, but not in 2006. Diel differences in the value of R vary with location and/or time of year: comparison of these vessels in other areas where pollock are surveyed during winter (Shumagin Islands, Shelikof Strait, Bogoslof Island) did not identify a diel change in R (De Robertis *et al.*, 2010), as observed during summer in the eastern Bering Sea.

Overall, in all situations where a significant vessel difference was observed, OD detected more pollock than MF, implying a weaker avoidance reaction to the noise-reduced vessel (Figure 10). The OD detected more pollock in the eastern Bering Sea at night. Measurements on winter prespawning pollock aggregations revealed that in two areas with shallower walleye pollock distributions (Shumagin Islands, fish depths $\sim 100 - 200$ m, and Shelikof Strait, 200 – 300 m), the OD detected ~ 31 and $\sim 13\%$ more pollock biomass as a result of the different fish-avoidance behaviour between vessels (Figure 10). In the Bogoslof area, where pollock are distributed deeper (at 400 – 700 m), acoustic estimates from the OD and the MF were not significantly different (Figure 10).

This day/night difference in vessel ratio R in the Bering Sea was not observed in the other locations where pollock reaction to the two vessels was studied (De Robertis *et al.*, 2010). In addition, the pattern in vessel differences among sites cannot be explained by fish depth alone; in the Bering Sea in summer, pollock are at the shallowest of any of the areas tested, but there is no vessel difference by day. At other locations, e.g. the Shumagin Islands and the
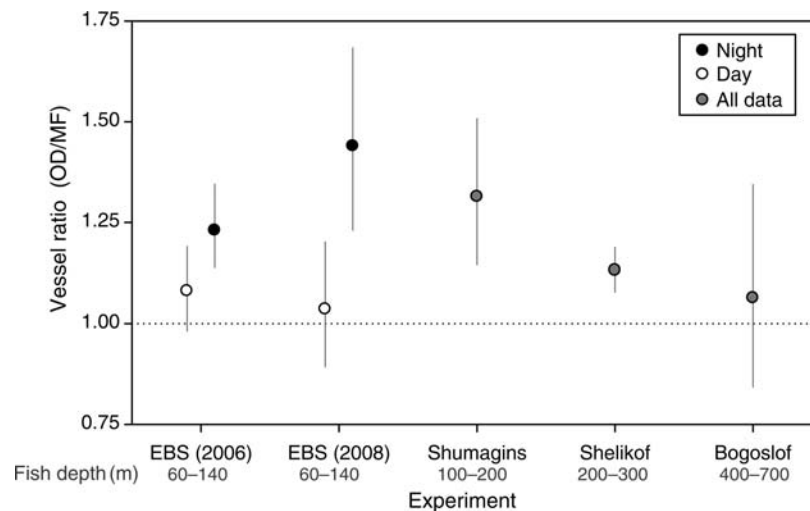
reaction to either vessel, simultaneous observations from the vessel-mounted echosounders confirm that pollock responded differently to the approach of OD and MF. This was not unexpected, because shipboard measurements are inherently less variable, being derived by averaging over much longer periods than from the buoy, which compare only a few seconds from each pass. As observed in a similar experiment in the Shumagin Islands (De Robertis and Wilson, 2010), OD detected significantly more backscatter and a greater TS of individual pollock than MF. The mean value of R during the experiment was 1.31 at 18 kHz and 1.41 at 120 kHz, similar to the value observed during side-by-side transects at night. Acoustic backscatter from fish with swimbladders such as pollock depends greatly on orientation (Nakken and Olsen, 1977; Hazen and Horne, 2004), and the lower value

Figure 10. Summary of all vessel comparisons of the OD and the MF on walleye pollock backscatter (this study; De Robertis *et al.*, 2008, 2010). Vessel ratios *R* (OD/MF) with 95% CIs for 38 kHz pollock backscatter are shown for each experiment. Day and night results are shown separately for the eastern Bering Sea (EBS), because there is a significant diel difference in that area only. Estimates where the lower confidence bound exceeds 1.0 indicate that the OD detects significantly more pollock backscatter than the MF. The approximate depth range of the walleye pollock in each experiment is shown in grey.

Shelikof Strait, pollock are deeper, but the OD detected significantly more than the MF. In all areas where there was a vessel difference, the value of *R* decreased with fish depth, consistent with a response to a stimulus propagating from the vessel at the surface.

The two existing comparisons of conventional and noise-reduced research vessels have reported conflicting results: Ona *et al.* (2007) reported that herring reacted almost twice as much to the noise-reduced "G. O. Sars" than to the conventional "Johan Hjort", with much of the reaction after vessel passage. In contrast, comparisons of MF and OD indicate that vessel ratios are variable, but when there are differences, the reaction is less to OD, the noise-reduced vessel. In interpreting these results, one needs to keep in mind the fact that the proposals that led to the construction of noise-reduced vessels (Mitson, 1995) were largely an attempt to influence how fish react to acoustic stimuli from vessels, rather than to make the vessels imperceptible. The proposals assumed that vessel noise (defined as sound pressure) 30 dB above the hearing threshold of fish would trigger a reaction. Under conditions of low background noise, fish such as walleye pollock with well-developed hearing can detect noise-reduced vessels at ranges of ~hundreds of metres (Mann *et al.*, 2009). Hence, noise reduction is not an attempt to make a vessel imperceptible to the fish being surveyed, but rather an attempt to influence how the fish react to the acoustic stimuli produced by the vessel.

The factors that influence how and why fish react to approaching vessels remain obscure. Fish often react to low-frequency sounds (Sonny *et al.*, 2006; Sand *et al.*, 2008), and reactions to sound depend on the information content of a signal, not just its absolute level (Schwartz and Greer, 1984; Engås *et al.*, 1995; Doksæter *et al.*, 2009). Many animals, including fish, respond to human-induced disturbances as though the disturbances represent a predator (Frid and Dill, 2002), and responses to predation risk may provide a useful analogy, because vessel-avoidance reactions by fish are likely to be triggered by stimuli perceived as a predatory threat. Many factors related to environmental conditions or the

internal state of fish and other animals, such as feeding history, maturity state, or exposure to predators, affect how animals respond to a predation risk (Lima and Dill, 1990; Lima, 1998). For example, feeding history and encounters with predators affect anti-predator behaviour; hungry organisms and those with little recent exposure to predators tend to be less risk-averse. In addition, the transmission of stimuli produced by a vessel to the fish depends on background noise, characteristics of the seabed, environmental conditions, and the relative locations of the vessel and the fish (Urick, 1982). Hence, the physiological state and recent experience of a fish, as well as the characteristics of the stimuli produced by a specific vessel and the factors affecting the transmission of stimuli, are likely to influence the reactions of fish to an approaching vessel.

Given the potential for complex interactions of multiple factors likely influencing decision-making by fish approached by vessels, it is unsurprising that current understanding of vessel avoidance is insufficient to explain the results of comparisons of noise-reduced and conventional vessels. For example, the heightened reaction of herring to a noise-reduced over a conventional vessel (Ona *et al.*, 2007), and the diel difference in reactivity of pollock to the MF and the OD in the Bering Sea, could not have been predicted *a priori* based on current understanding of how fish react to approaching vessels. Decision-making by animals is complex, so it will be extremely difficult to make predictions of avoidance behaviour that are sufficiently reliable to correct abundance measurements.

For the practical purpose of identifying and correcting survey biases, measurement of the impacts of behaviour on acoustic measurements is likely to be more tractable than accurately predicting the behaviour. Further development and adaptation of methods used to study the impacts of behaviour on acoustic measurements, such as measurement of Doppler shift (Holliday, 1974; Zedel *et al.*, 2003), the use of sonar (Soria *et al.*, 1996; Patel and Ona, 2009), horizontally pointed beams (Drastik and Kubecka, 2005), stationary echosounders (Olsen, 1990; Ona *et al.*, 2007), and vessel comparisons (Fernandes *et al.*, 2000;

De Robertis *et al.*, 2008, 2010) will likely lead to advances in our ability to quantify the impacts on abundance estimates of fish reactions to approaching vessels. The challenge will be to adapt these methods, which have been applied mainly in small-scale studies and restricted circumstances, i.e. under specific fish-aggregation patterns, to large-scale acoustic surveys, so that reactions to a vessel can be monitored routinely throughout a survey.

When conducting an acoustic survey, the reactions of fish to the vessel do need to be considered. For acoustic surveys of walleye pollock, this and previous studies (De Robertis and Wilson, 2010; De Robertis *et al.*, 2010) have led to the conclusion that, in some situations, the noise-reduced OD detects more backscatter from walleye pollock than the conventional MF. The current study was designed to detect vessel-specific behaviour rather than to determine the stimuli that cause such behaviour, but radiated noise is a reasonable hypothesis because the OD emits substantially less noise than the MF over the hearing range of pollock (De Robertis *et al.*, 2008; Mann *et al.*, 2009). However, the form of the relevant acoustic stimulus is unclear; consideration of vessel noise has focused primarily on sound pressure as measured in the far field, but other acoustic stimuli such as low-frequency particle motion may be more relevant to fish-avoidance reactions, particularly in the nearfield (Sand *et al.*, 2008). The diel and regional differences in avoidance behaviour reported here suggest that surveys can be timed for when and where the stock is least reactive, e.g. for walleye pollock in the eastern Bering Sea, during daylight. Overall, vessel-specific differences cannot be explained easily, likely because of the many interacting factors influencing the response. Nevertheless, it is clear that there is potential for a vessel effect, and biases may be introduced into a survey time-series when survey vessels are replaced (or if fish change their behaviour to the same vessel). To minimize these biases, new methods need to be developed to estimate the impact of behavioural reactions by fish to a survey vessel continuously.

Acknowledgements

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