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Analysis of vessel influence on spatial behaviour of fish schools using a multi-beam sonar and consequences for biomass estimates by echo-sounder

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Biases in the measurements of spatial distribution of fish schools and their consequences for school biomass estimates during conventional acoustic surveys are mainly due to vertical and lateral avoidance of the vessel. In this paper, we quantify school avoidance during an acoustic survey carried out from 13 to 29 May 1994 in the Catalan Sea. From a lateral multi-beam sonar the geometric characteristics (depth, length, width, height, surface, and volume) of 1268 schools were obtained. The 60 beams (1.5° × 15°) of the sonar scanned a vertical plane from 0° to 90°, perpendicular to the vessel path within a range of 100 m. Within this plane, the projected area ensonified by the echo-sounder used aboard for acoustic evaluation was evaluated to simulate a comparison between the sonar and the echo-sounder. The results have enabled us to improve our knowledge on the vertical and lateral avoidance patterns of schools in relation to their size, external structure, and their position in the water column, and to quantify the vessel influence on biomass estimated by echo-sounder.

Key words: acoustic, avoidance reaction, multi-beam sonar, school, stock assessment.

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Introduction

The acoustic observation on the spatial distribution of pelagic fish is often biased by the reaction of fish responding to the survey vessel (Olsen *et al.*, 1983), and the correction of the data for this bias, for spatial distribution as well as for biomass estimate, is essential. Combined techniques, using both echo-sounder and sonar, have already been suggested for the study of the behaviour of fish schools around the vessel (Lamboeuf *et al.*, 1983). The use of single-beam sonar in stock assessment has already been described (Bazigos, 1975). The sonar was mainly used for school counting during the acoustic survey, the beam being directed horizontally at 90° from the vessel route. The schools were then counted on a surface limited by two lines parallel to the transect, usually at a distance of 200 and 400 m from the transect line. This method was not a real success, probably because the actual volume sampled by the acoustic beam was not easy to evaluate (Forbes and Nakken, 1972). Close to the vessel (<100 m) the beam was too narrow to give an exhaustive view of the water volume, and at greater distances the horizontal stratification of the seawater temperature was responsible for "blind areas".

However, the recent availability of multi-beam sonars has allowed scientists to study school behaviour, mainly the reaction of schools to fishing boats (Aglen, 1985; Diner and Massé, 1987; Misund and Aglen, 1992). This paper presents results that indicate how vertical sounder information is biased and suggests a methodological use of multi-beam sonar in acoustic stock assessment methods.

Materials

The multi-beam sonar used was a Reson SEABAT 6012 with 60 beams of 1.5° (at −3 dB) each, and 15° in the perpendicular direction, surveying a total reception angle of 90°, while the corresponding emission angle was 120°. The sonar frequency was 455 kHz, with pulse length of 0.06 ms. The TVG function is adjusted at 20 log R. The range was fixed at 100 m but the efficient range was actually 80 m because of background noise over this distance. At this range the 60 beams were updated simultaneously seven times per second, that is,

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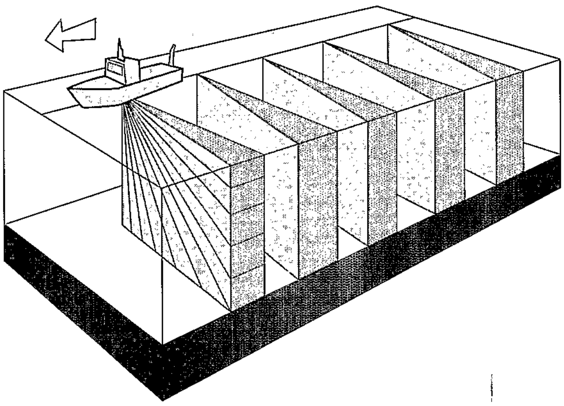

Figure 1. Diagram of the sonar sampling methodology (for clarity, the survey is represented with a very low sampling rate but during the survey the distance between transmissions was always lower than one metre).

at 5 knots vessel speed, one sample each 0.37 m along the vessel path. The image was a smoothing of two successive transmissions. The data obtained from the 90° sector ensonified were equivalent to 2D video images. Experiments (in experimental tank and at sea) with calibrated targets indicated that in a homogeneous acoustic field the sonar gives an acceptable uniformity in the distribution of brightness on the screen. The sonar head was set at 4 m depth to observe in the vertical plane so that it could record from 0° to 90° down and scan the side of the vessel route. We were thus able to explore the water column exhaustively on one side of the vessel (Fig. 1).

In this experiment, data were collected only during day-time (1700 to 1900 GMT) and from two acoustic surveys carried out in the Mediterranean Sea (Spain) from 19 to 26 May 1994 on board the RV "Garcia del Cid". The first data set was collected using a survey design with regularly spaced transects. The second data set was recorded during a 26 h station on a fish concentration near the Catalan coast (40°08′N and 00°30′W) at a depth less than 40 m. This last station consisted in repeating 13 rectangluar tracks (1.5 × 2.5 nmi) of 2 h each at around 5 knots vessel speed. The trawling hauls, made 2 d later all over these areas, indicated a dominance of small sardines (*Sardina pilchardus* W.) and anchovies (*Engraulis encrasicolus* L.).

Methods

The sonar data video images were recorded on S-VHS videotapes and then post-processed in our laboratory (Gerlotto *et al.*, 1994). Schools smaller than 5 m^2 were not considered. For each school, the greatest height (HMAX) and "width" (WMAX, perpendicular to the vessel path) and the distance between the centre of gravity of the school and the surface (DSURF) were measured. The distance from the centre of gravity of the school to the vertical line under the vessel sonar (DBCOR) was then computed. Owing to the low value of the beam angle in the vertical plane perpendicular to the vessel path (1.5°), no beam pattern correction was applied. The "length" of schools along the vessel path (LMAX) was estimated from the vessel speed and the total number of images counted. In this plane the reception beam angle is not negligible (15° at −3 dB) and therefore a beam-width correction related to the distance from the tranducer was applied on these estimated "lengths". The beam-width correction mainly used is (Johannesson and Losse, 1977): $Bc=2*R*tg(\alpha/2)$, where R is the distance from the boat and α the efficient beam angle. Thus, we obtained a corrected length: $LCOR=LMAX-Bc$.

The efficient sonar beam angle was estimated assuming that, apart from the vessel path (R>25 m), the shape of the school was not influenced by the vessel and therefore the LCOR versus WMAX scatterplot should be symmetrically distributed on each side of the bissectrix. Therefore, an empirical efficient beam angle (α) of 8° was obtained. This correction still provided a few negative length values. In order to correct them we had to assume that schools with LCOR/WMAX lower than 0.1 were overcorrected, as their length was shorter than the beam width. In these few cases (4%) we did not apply the beam correction and we assumed that LCOR= 0.1*WMAX. From these values the surface of the school cross-section (S) and the school volume VCOR were estimated assuming an ellipsoid shape (Squire, 1978).

We also used a vertical echo-sounder during this experiment (38 kHz, beam angle of 10°), mounted on a subsurface towed body on the same board as the sonar head. As no intercalibration between the sonar and the vertical echo-sounder was available, we did not compare quantitatively the exact data obtained by the two instruments. However, the limit of the vertical beam echo-sounder within the sonar beam range was plotted. Because of the radial orientation of the sonar beams, vertical and horizontal limits were added (at 55 m deep and at a distance of 70 m from the boat) in order to obtain a rectangular sampling volume. Once these limits were set we distinguished two areas. The first one (A1), close to the vessel, corresponded to half of the area ensonified by the vertical echo-sounder. The second one (A2) was the remainder of the area ensonified by the sonar (Fig. 2). After that, in each area the geometrical characteristics of schools and their distribution in the water column were measured and then compared.

A one-way analysis of variance (ANOVA) for unbalanced design was performed on the different school descriptors in order to test the influence of the lateral distance from the vessel. The range tests were carried out with the Duncan method.

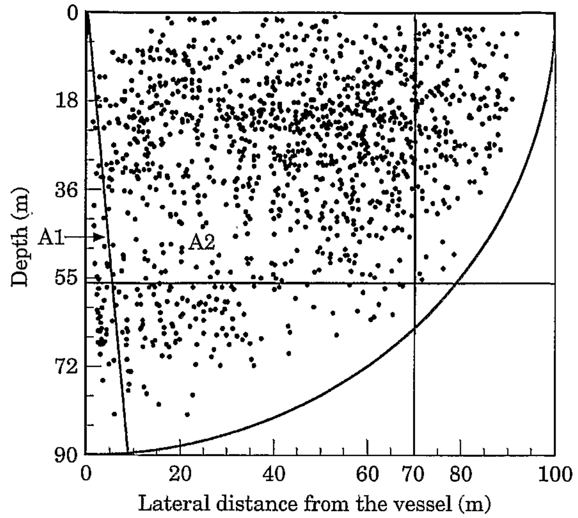

Figure 2. Projection in a vertical plane perpendicular to the vessel path of the 1268 school detections (close circles). A1 represents the simulated area ensonified by half of the echosounder beam. A1+A2 represents a limited rectangular area ensonified by the sonar.

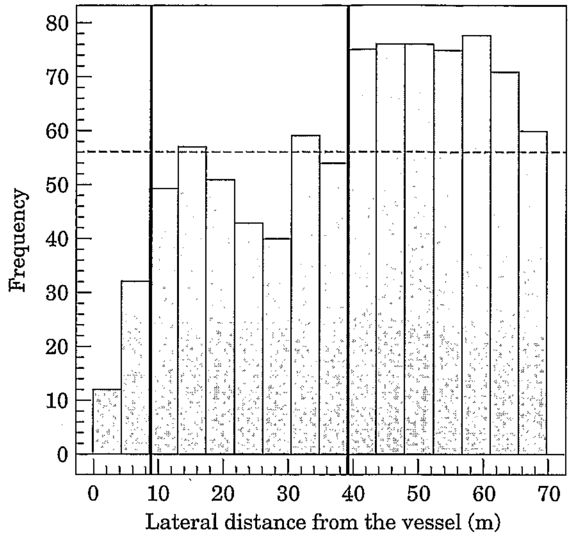

Figure 3. Frequency histogram of the lateral distances between the centre of gravity of the school and the vessel (DBCOR). Dashed line is the expected average under H_o; n=946.

Results

The sonar recorded 1268 schools. The DSURF versus DBCOR scatterplot is shown in Figure 2. Within the limits defined above, 933 schools were counted in the A2 area and 13 schools in the A1 area. Considering the area each instrument sampled, the number of schools per surface unit projected within the "virtual" vertical echosounder beam A1 (0.10 schools m^{-2}) was half that in the whole area A1+A2 (0.242 school m^{-2}).

The DBCOR frequency histogram (Fig. 3) shows a non-uniform distribution (χ^2=75, 9; p<0.001) of school frequency along this distance, contrary to what should be expected under the null hypothesis (H_o) of no lateral avoidance. There is a bimodal distribution of schools along this axis. The first mode, covering the class between 0 and 40 m, is characterized by few schools near the vessel (between 0 and 10 m) and a peak of values between 10 and 22 m. The second mode covers the class between 40 and 70 m and presents the highest frequencies. These results confirm that, during daytime, an important lateral school avoidance reaction occurs.

In area A1+A2, the mean DSURF per 10 m class of lateral distance from the vessel was computed (Fig. 4). The distance effect on the school depth was significant (ANOVA, F=2.51, p<0.02) and the DSURF mean of the distance class closest to the vessel (0–10 m) was significantly higher than all the other ones (Duncan test, p<0.05) except for the 50–60 m class (note that the A1 area is totally included in the first class (0.10 m)). In the same way, the distance effect on the log-transformed

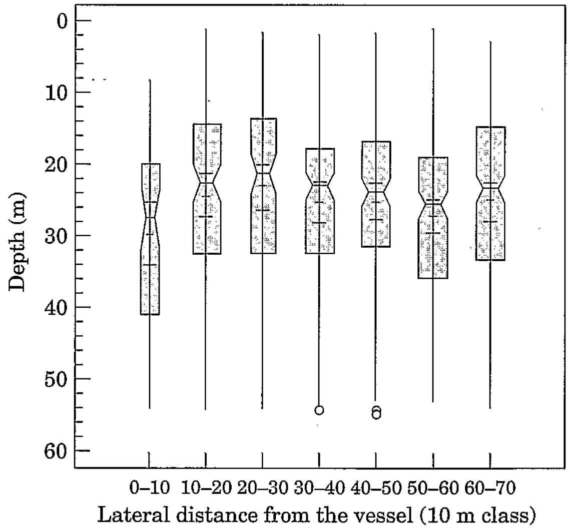

Figure 4. Box-whisker plot of the school mean depth versus the lateral distance from the vessel (10 m strata). The central box covers the middle 50% of the data value between the lower and upper quartiles. The width of the box is proportional to the square root of the number of observations. The notch corresponds to the width of a confidence interval for the median. The vertical bar inside the box represents one standard deviation around the mean. The "whiskers" extend out to the values that are within 1.5 times the interquartile range. Outlier points are plotted as separate points.

values of HMAX was highly significant (F=30.4, p<0.001) and the first two classes present significantly smaller HMAX mean values than all the others (Duncan test, p<0.04, Fig. 5). The distance effect on the log-transformed WMAX was also significant (F=5.65,

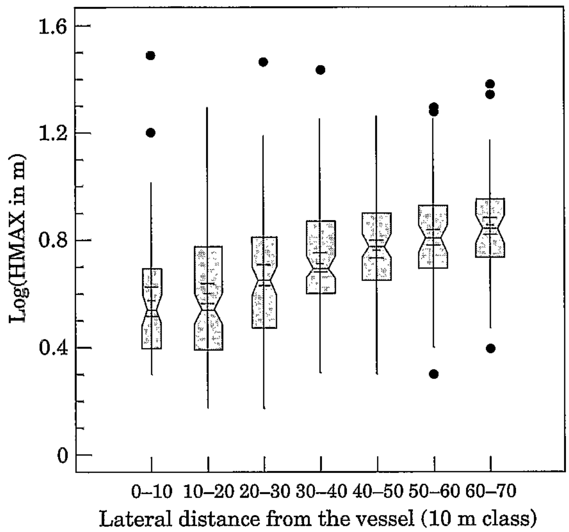

Figure 5. Box-whisker plot (see Fig. 4 for details) of the school mean height versus the lateral distance from the vessel (10 m strata).

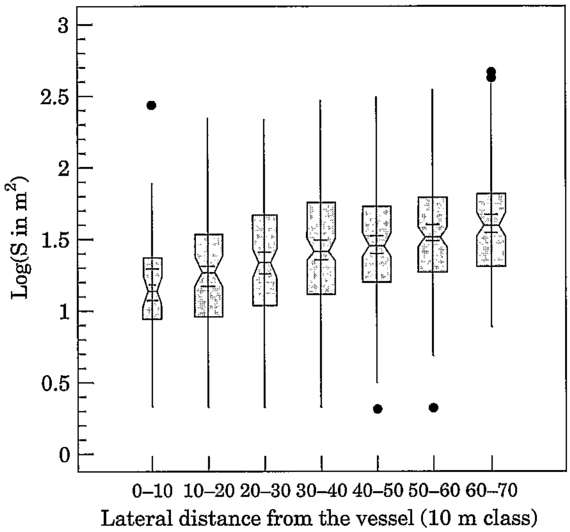

Figure 6. Box-whisker plot (see Fig. 4 for details) of the log-transformed mean school surface versus the lateral distance from the vessel (10 m strata).

$p<0.001$), but the range test indicates that neighbour distance classes can be grouped two-by-two, which indicates a more gradual effect of the distance from the boat on the school width. The distance effect on the log-transformed LCOR was not significant ($F=1.90$, $p=0.08$). Nevertheless, the relationship between LCOR and the lateral distance was sensitive to the beam angle correction. As expected, the lateral distance effect on log-transformed values of S and VCOR was significantly different ($F=16.7$, $p<0.001$ and $F=9.51$, $p<0.001$ respectively, Fig. 6) since these values were estimated from HMAX and WMAX. These results corroborate the hypothesis of a strong vertical school avoidance close to the hull of the vessel along with vertical compression (Fréon *et al.*, 1990). This vertical compression is associated with a horizontal one which seems to occur mainly in the direction perpendicular to the vessel path (WMAX).

Discussion

The general pattern of school frequency related to the lateral distance from the boat corresponds to the association of the alarm hearing threshold of fish, their flight speed, and their distance of reaction linked to the degree of disturbance by the vessel. The distribution of fish schools on the starboard side of the vessel (Fig. 3) allows us to make the following assumption: the fish school lateral avoidance reaction follows a double "wave-of-avoidance" pattern related to the distribution of the sound pressure gradient in front of the vessel (Fig. 7). The first wave would appear far away from the vessel, at the very moment the fish detect the sound pressure of the boat. At this stage, because of the acoustic shadow effect of the hull of the vessel, a first group of schools is trapped along the axis of the vessel path (Urick, 1975; Gerlotto and Fréon, 1988; Aglen and Misund, 1990). The second group escapes laterally and will then be detected by the lateral sonar far from the boat. This assumption corresponds to our results, since the average frequency of the schools far away from the boat (that is, between 40 and 70 m from the boat and up to 55 m deep) was significantly higher than the average frequency expected under the hypothesis of no lateral avoidance (70% instead of 56%, see Fig. 3). Then, while the boat is approaching, some of the schools trapped inside the acoustic shadow cone avoid the hull both laterally and vertically at a very short distance from the vessel. The others just dive when the boat passes over them. Thus, the lack of schools along the track of the boat (see Fig. 3) and the associated peak in schools frequency observed between 12 and 24 m would correspond to this near-field avoidance reaction.

Our results follow the schematic pattern of gradual reactions of fish. The more they detect sensory stimuli, the stronger is each additional stimulus intensity and the stronger is their reaction (Gerlotto and Fréon, 1990). In this classification, first the fish far away from the boat are disturbed by the sound of the propeller (Olsen, 1971) and so they react with a polarized position. This polarization induces a fast compression and enables the fish to avoid the disturbed area by a fast and coordinated movement of the school (Fréon *et al.*, 1993; Pitcher and Parrish, 1993). According to several authors, this avoidance reaction can appear far from the vessel (Neproshin, 1978; Schuijf and Hawkins,

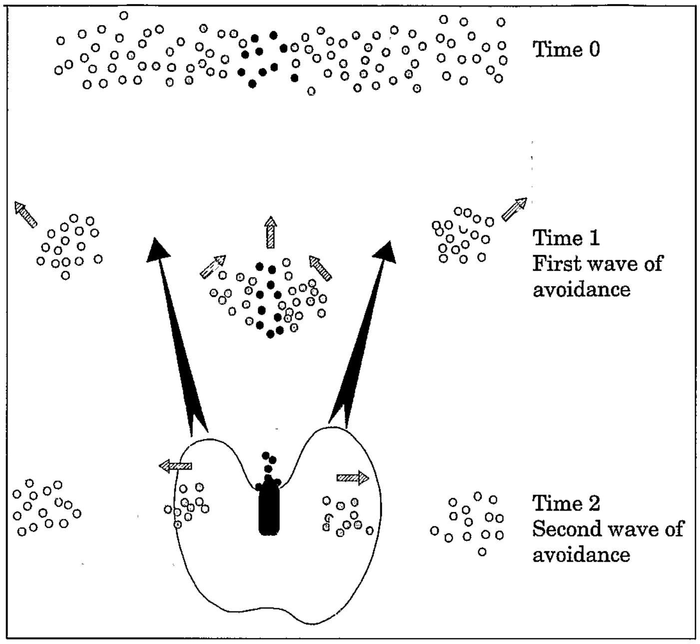

Figure 7. Schematic diagram of the "double wave of avoidance" mechanism. Time 0: schools far from the vessel; Time 1: schools at medium distance, first wave of avoidance; Time 2: schools below the vessel, second wave of avoidance. White dots: schools avoiding during the first wave. Grey dots: schools avoiding during the second wave. Black dots: schools actually recorded by the echo-sounder. Black arrows: propagation of sound. Striped arrows: movement of schools.

1983; Bercy and Bordeau, 1987; Mitson, 1993) and may involve up to 41% of the schools (Misund and Aglen, 1992). It is likely that our methodology underestimates the total avoidance, since lateral avoidance reaction over 80 m from the vessel path cannot be measured. Secondly, confronted with an impending contact with the hull of the boat, fish escape in the direction opposite to the disturbing visual source either by diving under the hull (Fig. 4) or by escaping laterally. The upper part of the school is compressed, which explains the disparity in school height and shape observed in Figures 5 and 6. This flight reaction is linked to the hull operating as a visual releaser and, in the case of pelagic fish, it could appear at a few metres from them. In this case, the flight distance is a function of the minimum approach distance of the species but can vary either with several abiotic factors (turbidity and temperature) or biotic factors (visual capabilities, past learning experiences (Goodey and Liley, 1986; Soria *et al.*, 1993) or physiological stage).

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References

Aglen, A. 1985. Sonar observations of the behaviour of herring schools relative to a fishing vessel. ICES-FAST Working Group, Tromsoe, May 1985: 7 pp. (mimeo).

Aglen, A. and Misund, O. A. 1990. Swimming behaviour of fish schools in the North Sea during acoustic surveying and pelagic sampling trawling. ICES CM 1990/B: 38, 8 pp.

Bazigos, G. P. 1975. The statistical efficiency of echo surveys with special reference to lake Tanganyika. FAO Fisheries Technical Paper, 139. 43 pp.

Bercy, C. and Bordeau, B. 1987. Effects of noise radiated by tuna fishing boats on fish behaviour. International Symposium on Fisheries Acoustics, 22–26 June, Seattle, Washington, E.U., Contribution 8b. 12 pp.

Diner, N. and Massé, J. 1987. Fish school behaviour during echo survey observed by acoustic devices. ICES CM 1987/B: 30, 28 pp.

Forbes, S. T. and Nakken, O. 1972. Manual of methods for fisheries resources surveys and appraisal. Part 2. The use of acoustic instruments for fish detection and abundance estimation. FAO Manual of Fisheries Sciences, 5. 138 pp.

Fréon, P., Gerlotto, F., and Soria, M. 1990. Evaluation of the influence of vessel noise on fish distribution as observed using alternatively motor and sails aboard a survey vessel. ICES CM 1990/B: 55, 15 pp.

Fréon, P., Gerlotto, F., and Soria, M. 1993. Variability of *Harengula* spp. school reactions to boats or predators in shallow water. ICES Marine Science Symposia, 196: 30–35.

Gerlotto, F. and Fréon, P. 1988. Influence of the structure and behaviour of fish schools on acoustic assessment. ICES CM 1988/B: 53, 31 pp.

Gerlotto, F. and Fréon, P. 1990. Review of avoidance reactions of tropical fish to a survey vessel. ICES/FAST Working group Meeting, Rostock, April 1990. 10 pp.

Gerlotto, F. Fréon, P., Soria, M., Cottais, P-H., and Ronzier, L. 1994. Exhaustive observation of 3D school structure using multibeam side scan sonar: potential use for school classification, biomass estimation and behaviour studies. ICES CM 1994B: 26, 12 pp.

Goodey, W. and Liley, N. R. 1986. The influence of early experience on escape behaviour in the guppy. Canadian Journal of Zoology, 64: 885–888.

Johannesson, K. A. and Losse, G. F. 1977. Methodology of acoustic estimations of fish abundance in some schools. UNDP/FAO Resource Survey Projects. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 170: 296–318.

Lamboeuf, M., Burczynski, J., Bencherifi, M., Chbani, M., and Elminowicz, A. 1983. Evaluation acoustique de la biomasse des stocks de sardine au Maroc de 1979 à 1981. Combinaison des estimations du sonar et du sondeur vertical. FAO Fisheries Report, 300: 197–207.

Misund, O. A. and Aglen, A. 1992. Swimming behaviour of fish schools in the North Sea during acoustic surveying and pelagic trawl sampling. ICES Journal of Marine Science, 49: 325–334.

Mitson, R. B. 1993. Underwater noise radiated by research vessels. ICES Marine Science Symposia, 196: 147–152.

Neproshin, A. Y. 1978. Behaviour of pacific mackerel, *Pneumatophorus japonicus*, when affected by vessel noise. Journal of Ichthyology, 18: 695–699.

Olsen, K. 1971. Influence of vessel noise on behaviour of herring. *In* Modern Fishing Gears of the World, pp. 291–294. Ed. by H. Kristjonsson, Fishing News Books, London.

Olsen, K., Angell, J., Pettersen, F., and Lovi, A. K. 1983. Observed fish reactions to a surveying vessel with special reference to herring, cod, capelin and polar cod. FAO Fisheries Report, 300: 131–138.

Pitcher, T. J. and Parrish, J. K. 1993. Functions of shoaling behaviour in teleosts. *In* The behaviour of teleost fishes, 2nd ed., pp. 363–427. Ed. by T. Pitcher. Chapman and Hall, London. 715 pp.

Schuijf, A. and Hawkins, A. D. 1983. Acoustic distance discrimination by the cod. Nature, 302: 143–144.

Soria, M., Gerlotto, F., and Fréon, P. 1993. Study of learning capabilities of tropical clupeoids using an artificial stimulus. ICES Marine Science Symposia, 196: 17–20.

Squire, J. L. 1978. Northern anchovy school shapes as related to problems in school size estimation. Fisheries Bulletin, US, 76: 743–748.

Urick, J. J. 1975. Principles of underwater sound for engineers. McGraw Hill, New York, 2nd ed. 384 pp.