

## Sonar observations of schooling herring: school dimensions, swimming behaviour, and avoidance of vessel and purse seine

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Horizontal dimensions and swimming and avoidance behaviour of herring schools were quantified by means of a multi-beam, true-motion sonar. The schools were usually elliptical with an average length to width ratio of about 1.5:1. A relationship between the school biomass and the average school area was established. Individual schools maintained a fairly consistent swimming pattern, but there were great variations between schools. In about 70% of the cases the schools avoided the vessel horizontally, and vertical avoidance was observed when the vessel passed over the schools. Avoidance behaviour was most apparent with spawning, migrating schools, and was consistent with the generalized emission pattern of vessel-generated sound. The herring were usually easy to capture in winter darkness, but they escaped capture in 36% of the sets in summer daylight. Limitations of multi-beam sonar for the study of fish schools are discussed.

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### Introduction

A fish school appears as a rather compact unit with individuals in synchronized and polarized swimming patterns (Pitcher, 1983). Schooling behaviour may, however, change with season, life stage, and physical environment (Mohr, 1971; Radakov, 1973). To reveal changes in school size and swimming behaviour, herring schools were studied in different seasons and geographical areas by use of the Simrad SM 600 sonar (Bodholt, 1982).

The herring senses low-frequency sound (Olsen, 1976; Blaxter *et al.*, 1981; Schwarz and Geer, 1984), has a certain directional hearing (Olsen, 1969), and can probably detect the distance to the sound source (Blaxter, 1985). Characteristic of sound generated by diesel-engined steel-hulled vessels are the dominance of low frequencies (Gjestland, 1968; Freytag and Karger, 1969) and a certain pattern of emission (Urick, 1967).

According to an avoidance-behaviour model (Olsen *et al.*, 1983a), an instantaneous increase in the sound pressure gradient will trigger a horizontal avoidance reaction to the approaching vessel. The model predicts that the fish will increase swimming speed and move more radially away from the vessel with a downward component as the distance decreases. Just before and as the vessel passes over, the fish will show sudden escape

reactions. The strength of the reaction depends upon the depth of the fish and the vessel speed. An attempt is made to relate the avoidance behaviour of schooling herring to this model.

Frequently, herring schools avoid purse-seine capture. According to von Brandt (1984) the pursuing phase is critical, and this operation was studied to reveal the fish-to-gear reaction. Catch information was collected from several purse seiners so that the capture success rate could be estimated.

### Materials and methods

Recordings by the Simrad SM 600 were made from two purse seiners (Table 1) during the winter fishery for Norwegian spring-spawning herring in 1985 and 1986, and during the summer fishery for North Sea herring in 1984 and 1985 (Fig. 1).

The schools were recorded either when the vessel circled clockwise with the schools on the starboard side (38 cases), or when the vessel steamed towards and passed over them (67 cases). The vessel circled the schools with a speed around 2.5 m/s (5 knots) at a horizontal distance of about 200 m, and passed over the schools with a speed around 3.6 m/s (7 knots). The schools encircled were observed from 3 to 25 min, and it

Table 1. Vessels and gear used on the sonar recording cruises (GRT: gross registered tonnage, hp: horse power).

Name	Vessel			Purse-seine			
	Length (m)	Tonnage (GRT)	Engine (hp)	Length (m)	Depth (m)	Mesh size (mm)	Lead (kg)
"Klaring" .....	50.6	457	1040	602	163	31.5	4050
"Libas" .....	73.8	1348	3600	597	163	20.3	5000

took 0.5 to 3 min for the vessel to pass over a school. North Sea herring were recorded only in daylight, while Norwegian spring-spawning herring were mainly recorded at night. During night observations, the vessel used regulation lights only.

The sonar recordings were stored on videotape via a palcoder (COX PAL 153 WS/GS) connected to the R-G-B outputs of the sonar, and later displayed by a JVC video system (Model CR-6600E). The movements of the school ( $Y_n$ ) and the vessel ( $X_n$ ) were drawn on transparencies by marking the midpoint of the school projection ( $y_n$ ) and the vessel symbol ( $x_n$ ) at intervals of

10 or 30 s as the vessel passed over or circled the school, respectively (Fig. 2). The size of the school projection was measured across the beams ( $cw_n$ ) and along the beams ( $lw_n$ ). Horizontal distance ( $R_n$ ), depth of the school ( $D_n$ ), and vessel speed ( $S_n$ ) calculated by the sonar computer were noted, and the following parameters quantified:

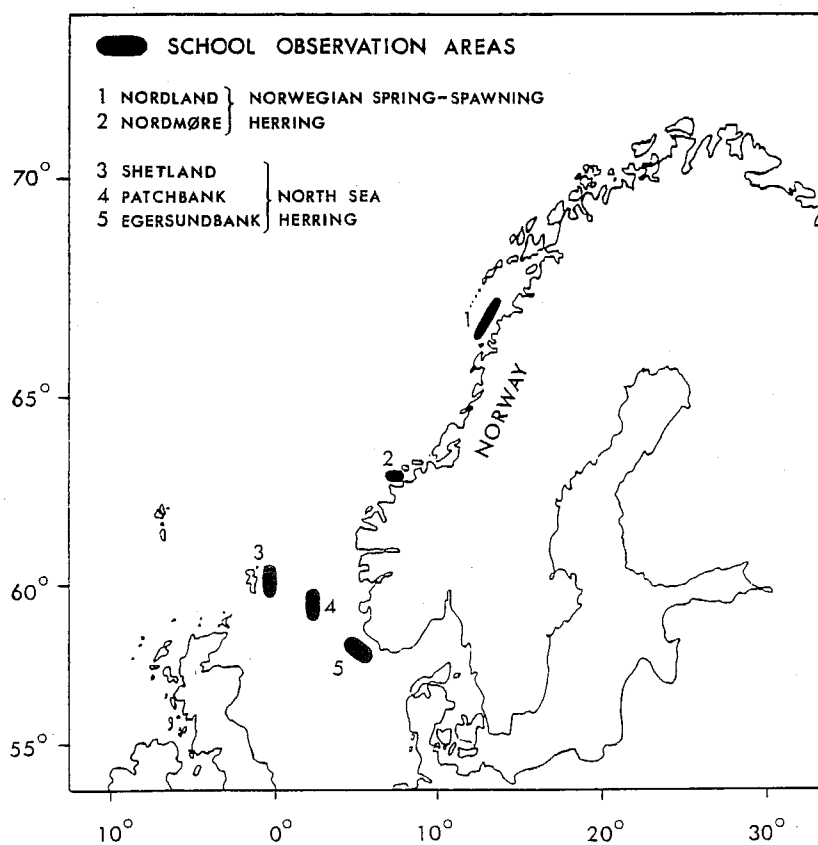


Figure 1. Geographical locations of herring schools recorded during 1984-1986.

<sup>a</sup> Crosswise extent	$CW_n = cw_n s - 2R_n \tan B/2$	(m)	(1)
<sup>a</sup> Lengthwise extent	$LW_n = lw_n s - c \tau/2$	(m)	(2)
<sup>a</sup> School area	$A_n = (LW_n CW_n/4) \pi$	(m <sup>2</sup> )	(3)
Horizontal swimming speed	$Vh_n = Y_n s/t$	(m/s)	(4)
Vertical swimming speed	$Vv_n = -(D_n - D_{n-1})/t$	(m/s)	(5)
Radial swimming direction	$\alpha_n$	(°)	(6)
Radial hor. swimming speed	$Vhr = Y_n \cos \alpha_n s/t$	(m/s)	(7)
Direction of bearing	$\beta_n$	(°)	(8)

$$\text{Index of horizontal movement IHM} = HD / \sum_{i=1}^n Y_n \quad (9)$$

- a: Calculated for encircled schools only;
- s: Scaling factor (sonar dist./dist. on monitor screen);
- B: Width of single sound beam (5° on transmitter);
- c: Speed of sound (~1500 m/s);
- $\tau$ : Pulse length (4 ms with sonar range = 250 m);
- HD: Horiz. distance between first and last school position.

Horizontal swimming speed of the schools encircled was averaged for the first 5 min ( $Vh_{5 \text{ min}}$ ), for the total time of observation ( $Vh_{\text{tot}}$ ), and when the purse seine was shot ( $Vh_{\text{shot}}$ ). The depth of the school centre recorded by the echo sounder was used to calculate vertical swimming speed as the vessel passed over. The pattern of movement of the school was quantified by the index of horizontal movement (IHM), which is close to 1 if the school moves in a straightforward pattern and close to 0 if the school moves in a circular pattern. IHM was measured for the first 5 min ( $IHM_{5 \text{ min}}$ ), for the total observation time ( $IHM_{\text{tot}}$ ), and when the purse seine was shot ( $IHM_{\text{shot}}$ ).

The net depth during the sets was recorded by a Scanmar 4001 sensor at one of the middle purse-ring bridles. The biomass of schools caught was estimated on the basis of the catch volume in the fish holds; and length to the nearest 0.5 cm below; gonad maturation and stomach volume stages were recorded from samples of 100 specimens. Based on information from 39 purse seiners from 1984 to 1986, the catch success rates (% of the sets with catch) were compared for the different herring fisheries.

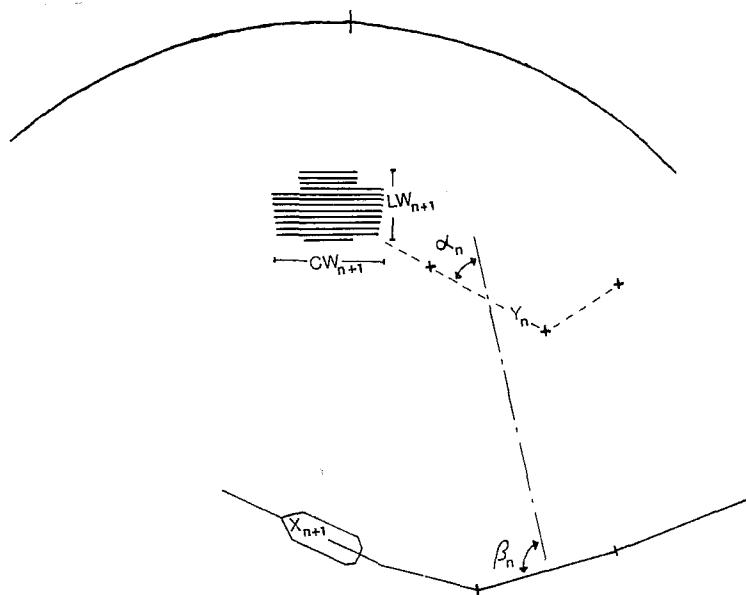


Figure 2. Analysis of the sonar display ( $cw_{n+1}$ : crosswise extent,  $lw_{n+1}$ : lengthwise extent,  $x_{n+1}$ : vessel position,  $Y_n$ : movement of school in an observation interval,  $\alpha_n$ : radial swimming direction,  $\beta_n$ : vessel-to-school direction of bearing).

Table 2. Average area and shape of herring schools (CW: crosswise, LW: lengthwise,  $r_s$ : Spearman's rank correlation coefficient, n: no. of measurements, ns: no. of schools).

Herring population	School area (m <sup>2</sup> )	School shape		n	ns
		CW:LW	$r_s$		
Norwegian spring-spawning	5355.9	1.70:1	0.76	91	5
North Sea	2301.8	1.52:1	0.59	795	33

Table 3. Average horizontal (Vh) swimming speed of herring schools (bl/s: body length/s, MW-test: Mann-Whitney test).

Fishing ground	Schools encircled				Schools passed over				MW-test p
	Vh m/s	bl/s	s.d. m/s	n	Vh m/s	bl/s	s.d. m/s	n	
Nordland	—	—	—	—	1.94	5.2	0.91	107	—
Nordmøre	0.87	2.5	0.55	91	1.49	4.2	0.90	33	<0.01
Shetland/Patchbank	0.78	2.8	0.45	359	1.13	4.0	0.73	97	<0.01
Egersundbank	0.75	2.8	0.42	370	1.40	5.2	0.75	93	<0.01

## Results

The recorded Norwegian spring-spawning herring averaged 35.5 cm, were mature, and had empty stomachs. The North Sea herring averaged 27.2 cm, were maturing, and had full stomachs.

### Horizontal dimensions

The average area of the Norwegian spring-spawning herring schools was larger than that of the North Sea herring schools (Table 2). On the spawning grounds off western Norway, layers too wide in extent to be measured by the sonar method were encountered.

The crosswise extent of the school projection was usually in the swimming direction and was on average 1.5 times the lengthwise extent. In addition, quite strong correlations between these dimensions indicate an elliptical school shape (Table 2). The average school area (Y) was linearly related to the biomass (X) of whole schools caught in the North Sea (Fig. 3):

$$Y = 37.8X - 85.1 \quad (r = 0.97, p < 0.05, n = 6).$$

A similar relationship may exist for Norwegian spring-spawning herring as indicated by the two measurements given in Figure 3. Relatively, the variation in the school area was about half of the average (average coefficient of variation = 0.59, n = 38).

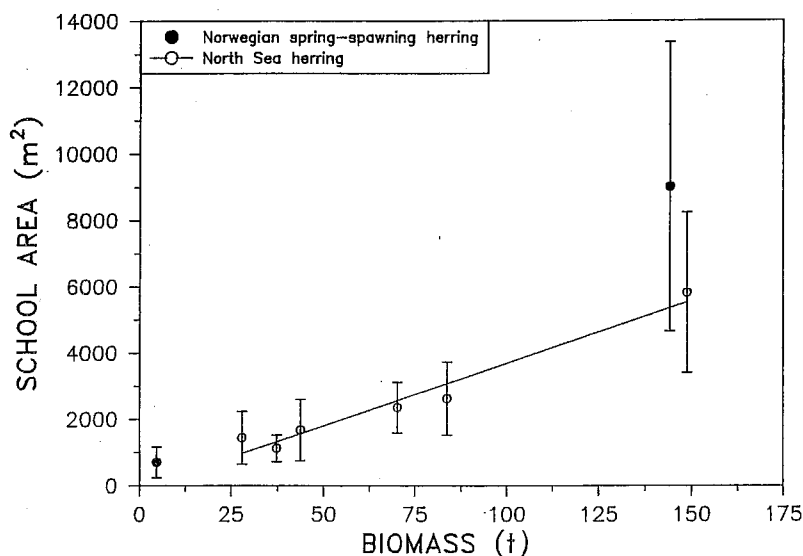


Figure 3. Catch biomass of whole schools related to average school area (vertical bars: standard deviation).

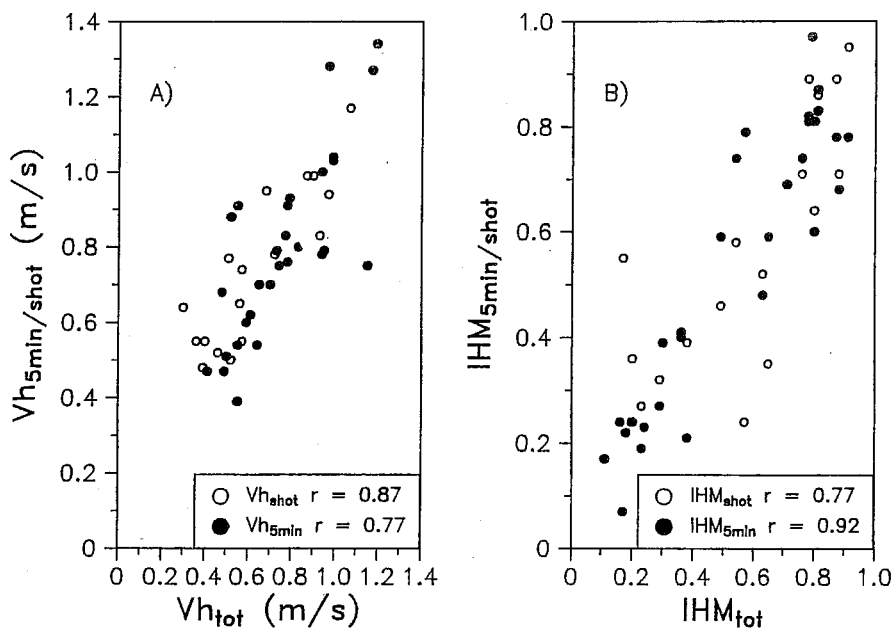


Figure 4. A) Average horizontal swimming speed for total time of observation ( $V_{h_{tot}}$ ) related to the average for the first five minutes ( $V_{h_{5min}}$ ) and during shooting ( $V_{h_{shot}}$ ). B) Index of horizontal movement for the total observation time ( $IHM_{tot}$ ) related to the index for the first five minutes ( $IHM_{5min}$ ) and during shooting ( $IHM_{shot}$ ).

### Swimming behaviour

The schools were swimming at an average depth of about 60 m in the Nordmøre fjords and the North Sea, and 130 m off Nordland. Average horizontal swimming speeds were about 0.8 m/s for the schools encircled (Table 3), but significantly faster for the schools passed over. Similarly, the variation in the swimming speeds increased when the vessel passed over. Maximum horizontal speed (one example) was 17.1 body lengths/s for a 10-s interval.

Both average horizontal swimming speed and index of horizontal movement varied among the schools, but they remained fairly constant for different time intervals for individual schools (Fig. 4A,B). This indicates that the individual school moved in a fairly consistent pattern. The pattern of movement was independent of the school size since there was little correlation between  $IHM_{tot}$  and the school area ( $r = -0.08$ ,  $n = 33$ ).

### Vessel avoidance

There were twice as many observations of radial swimming direction ( $\alpha$ ) away from as towards the vessel by both manoeuvring methods (527 against 253, and 195 against 106). Average radial swimming directions of  $327^\circ$  and  $355^\circ$ , respectively, indicate some guiding of the schools, both when the vessel circled or steamed over the schools (Fig. 5A,B). However, there were great angular deviations (Zar, 1974) of  $87.7^\circ$  and  $102.6^\circ$  when the vessel circled or passed over the schools respectively.

Average radial horizontal swimming speeds were around 0.2–0.3 m/s away from the vessel (positive  $V_{hr}$ ), and there were no differences in this speed for the schools encircled or passed over (Table 4). The schools passed over off Nordland avoided the vessel radially with a faster speed, and they dived (negative  $V_v$ ) clearly with an average speed of 0.27 m/s. General diving was not recorded on the other fishing grounds.

Significant correlations between horizontal swimming behaviour and vessel-to-school distance indicate that horizontal avoidance seemed to increase as distance increased (Table 5). As only 2 out of 43 schools were not recorded by the echo sounder, there seemed to be little sideways avoidance before the vessel passed over. Systematic diving by the schools was only recorded when the vessel passed straight over them (Figure 6A), and at this moment the average diving speed was 0.47 m/s. Diving speed was independent of depth since there was no correlation between the sum of the vertical swimming speeds and the average swimming depths (Table 5). There was also no correlation between the avoidance behaviour and the speed of the vessel (Table 5).

There were negative correlations between the horizontal swimming parameters and the direction of bearing ( $\beta$ ) (Table 5), and a rather strong tendency for radial horizontal swimming speed (Fig. 6B). This indicates that the horizontal avoidance ceased when the pressure gradients given in the sound emission pattern of vessels (Urlick, 1967) were decreasing.

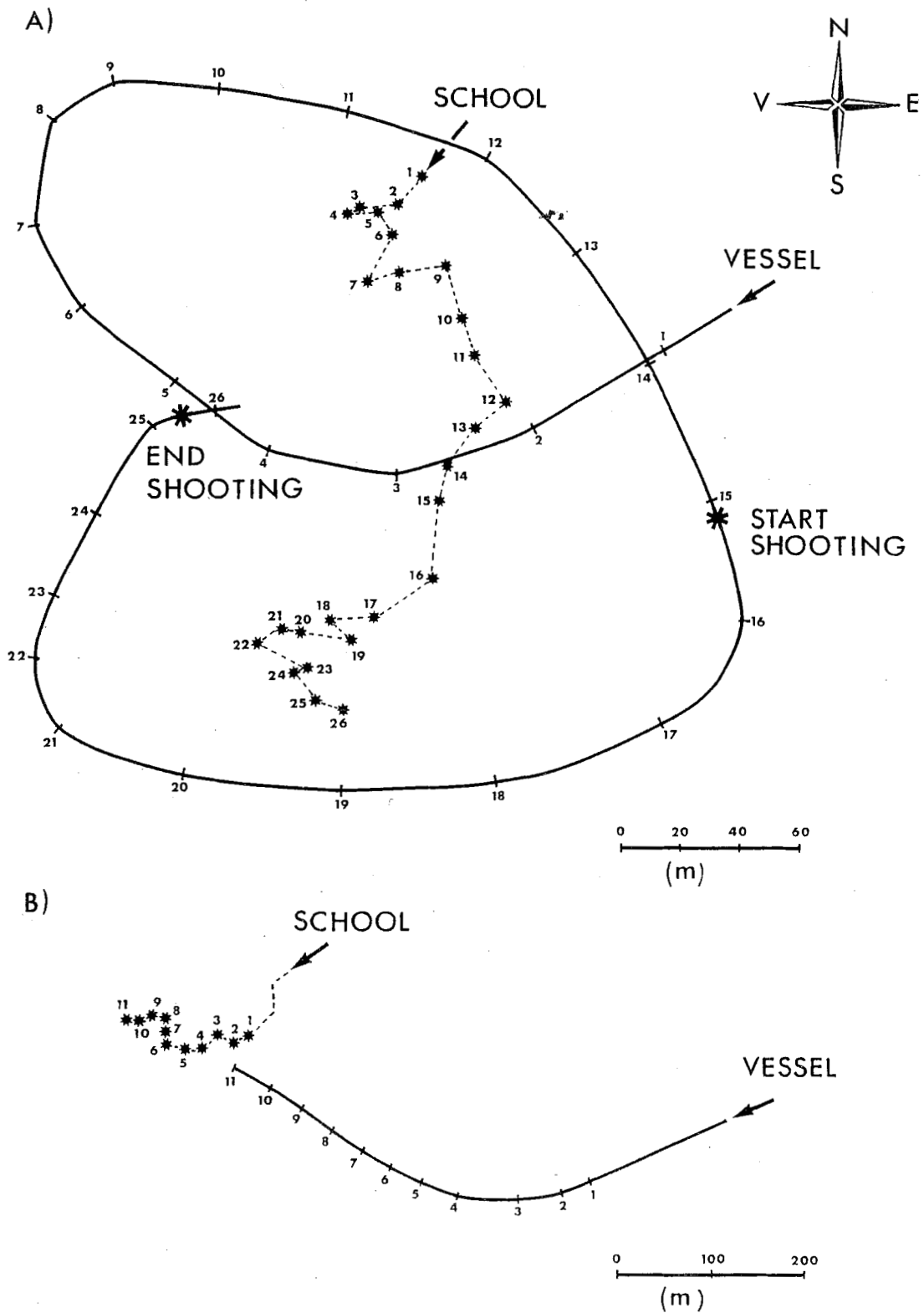


Figure 5. Typical patterns of horizontal movement. A) School avoiding circling vessel (1–5, 16–23), but continuing in a particular direction. B) Vessel passing over school which is avoiding, but swimming in the same direction as, the vessel. Observation interval: A) 30 s, B) 10 s.

Table 4. Average radial horizontal (Vhr) and vertical (Vv) swimming speed of herring schools (MW-test: Mann-Whitney test).

Fishing ground	Schools encircled				Schools passed over				MW-test p
	Vhr m/s	n	Vv m/s	n	Vhr m/s	n	Vv m/s	n	
Nordland	-	-	-	-	0.79	107	-0.27	144	-
Nordmøre	0.34	84	-0.03	75	0.13	33	0.02	42	>0.10
Shetland/Patchbank	0.21	348	0.01	366	0.30	97	0.01	124	>0.10
Egersundbank	0.25	343	-0.02	379	0.32	94	-0.01	165	>0.10

### Purse-seine avoidance

The Norwegian spring-spawning herring were captured in all observed sets (Fig. 7), while the North Sea herring schools escaped capture in about 50 % of the observed sets. Five schools escaped under the sinking net before pursing started, while six schools escaped under the vessel during pursing. On four occasions schools divided, and one sub-school escaped under the vessel, while the other was captured.

There seems to be a connection between the school dividing, the escapement under the vessel, and the beginning of the leadline lifting (Fig. 7). In this phase some of the schools on the Egersundbank showed a dramatic upwards swimming, recorded at up to 0.58 m/s, and they seemed to "explode" at the surface, with individuals whirling around at high speed as long as the pursing lasted. There were many dead individuals in the net, and some by-catches of preying saithe. Along the Norwegian coast there were by-catches of preying cod.

The catch success was about 90 % during the winter fishery for Norwegian spring-spawning herring and about 64 % during the summer fishery for North Sea herring (Table 6).

## Discussion

### Limitations of multi-beam sonar

The sound-beam directability and pulse length put limitations on the resolution capability of a sonar (Wilkins,

1986), and the sonar projection of a school might be distorted and overestimated, with the midpoint of the projection different from the real one (Fig. 8). With regard to area measurements, resolution errors should be corrected by adjusting for beamwidth and pulse length (Anon., 1975).

The precision of depth measurements of a school by sonar is illustrated in Figure 9. At a certain distance the first weak echo of an imaginary circular school with radius  $r$  is obtained by tilt angle  $a_1$ . To get the correct position of the school midpoint the transducer must be tilted down to angle  $a_2$ . In general for small tilt angles and long ranges, the distance measurement error will be rather limited, but the depth measurement error may be as large as the vertical extent of the school. The relationship will be the opposite for large tilt angles and short ranges. In addition, gradients in the speed of sound profile may deflect the emitted sound beam (Smith, 1977) and result in serious errors in the depth measurements of schools. Because the recordings were carried out at a relatively short range, deflection-induced errors were minimal (Halvorsen, 1985).

### Horizontal dimensions

The schools of mature Norwegian spring-spawning herring were about twice the size of the schools of feeding North Sea herring, probably reflecting variation in school size with stage of life history (Devold, 1969; Mohr, 1971).

In calculating the school area, the schools were con-

Table 5. Swimming behaviour rank-correlated with horizontal distance, depth, vessel speed, and direction of bearing ( $r_s$ : Spearman's rank correlation coefficient, NS: not significant).

	Schools encircled			Schools passed over		
	Distance $r_s$	Speed $r_s$	Bearing $r_s$	Distance $r_s$	Speed $r_s$	Depth $r_s$
Vh	0.19	0.08	-0.17	0.14	-0.05 (NS)	
Vrh	0.16	0.02 (NS)	-0.47	0.18	0.05 (NS)	
Vv	0.01 (NS)	-0.09 (NS)		0.19	0.01 (NS)	
$\Sigma Vv$						0.22 (NS)
N	775	775	775	475	475	70

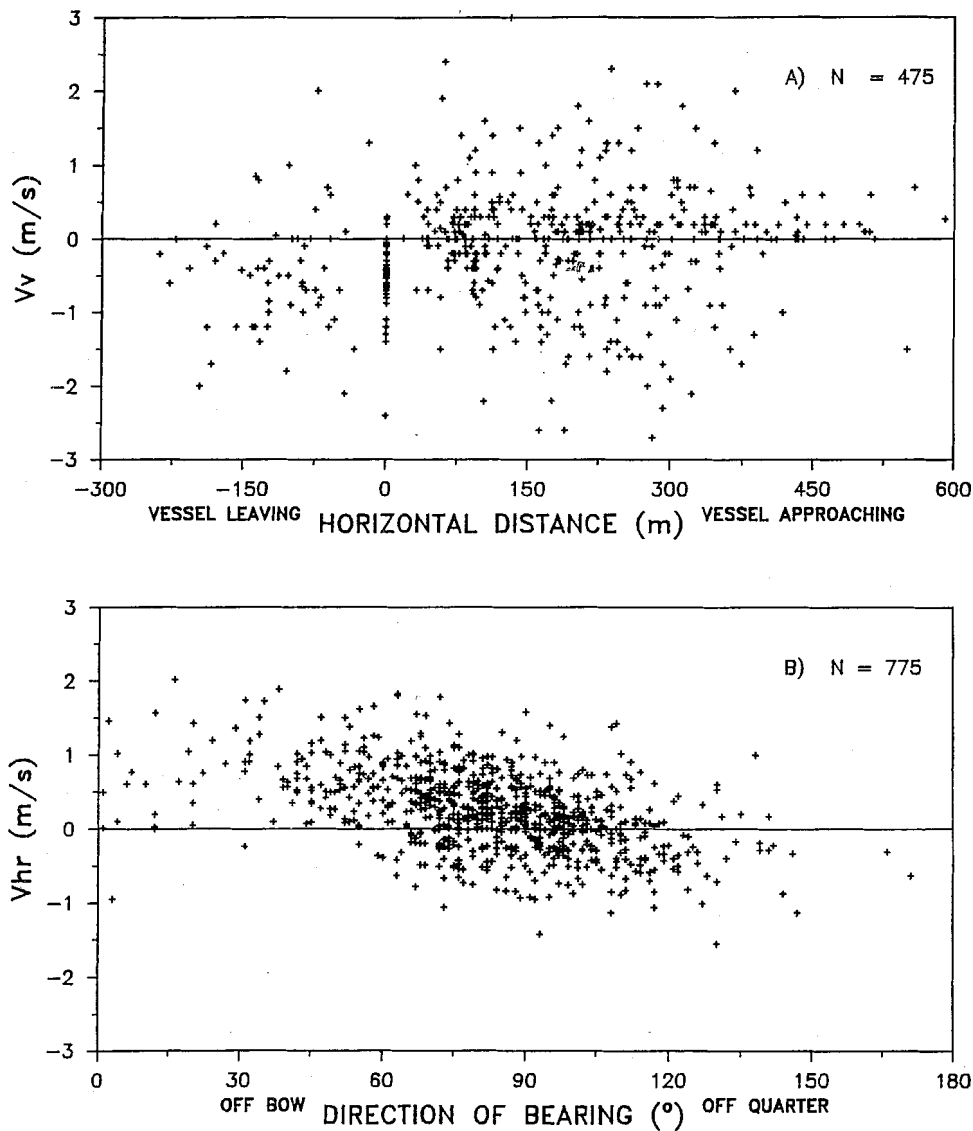


Figure 6. A) Vertical swimming speed ( $V_v$ ) related to horizontal vessel-to-school distance. B) Radial horizontal swimming speed ( $V_{hr}$ ) related to vessel-to-school direction of bearing.

sidered elliptical (Equation (3)), which is a common shape for both herring and sardine (Bolster, 1958; Cushing, 1960). The sonar projections were mostly quadrangular, which transforms to an elliptical shape when the distortion and the connection between horizontal extents are taken into account. The crosswise-to-lengthwise proportions of about 1.5:1 indicate that the elliptical schools were longer than they were wide, as the crosswise extent was usually in the swimming direction. Similar proportions are observed for sardine and mackerel schools off India (Anon., 1974). Anchovy schools off California were more irregular in shape even if many were elliptical (Squire, 1978).

There was a distinct variation in the area measurements, which were equal to about half the size of the average school area. The variation may arise from varying lacunae between sub-units of the school (Pitcher and Partridge, 1979), and changes in swimming speed that result in tightening (Partridge *et al.*, 1980) or loosening (Breder, 1959; Radakov, 1973) of the school structure. Changes in aspect angles which result in varying target strengths (Mitson, 1983) may also influence the size of the projected area. If parts of the school are not ensounded, the projected area may decrease.

There was a linear relation between the average area and the biomass of the schools. This is reasonable be-



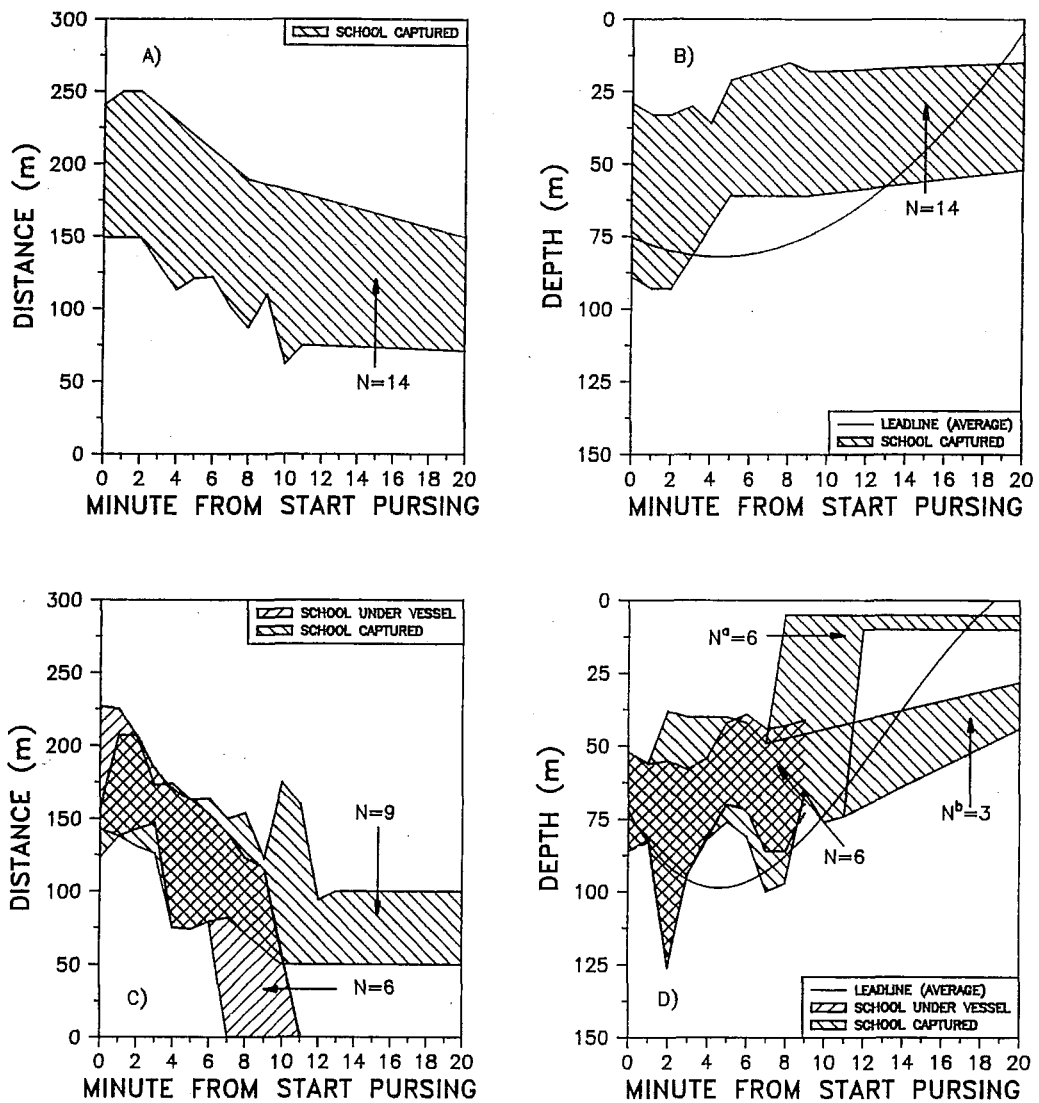


Figure 7. Interval of variation for horizontal vessel-to-school distance and swimming depth during pursuing. A, B) Norwegian spring-spawning herring. C, D) North Sea herring. (N: number of observations, N<sup>a</sup>: Patchbank, N<sup>b</sup>: Egersundbank).

cause of the herring school structure, which gives a school volume proportional to the number of individuals and the cube of the average body length (Pitcher and Partridge, 1979). According to this, the area of a horizontal section through the school is proportional to the number of individuals in the section and the square of

the average body length. The linear relation indicates that the school extension increases faster horizontally than vertically, perhaps owing to the influence of environmental factors such as light level, sea temperature, and vertical distribution of prey, on the formation of the school (Radakov, 1973).

Table 6. Capture success rate (CSR) in herring purse seining.

Herring population	Fishing season	CSR (%)	n	Chi-squared test (p)
Norwegian spring-spawning	Winter darkness	89.3	84	<0.05
North Sea	Summer daylight	63.7	311	

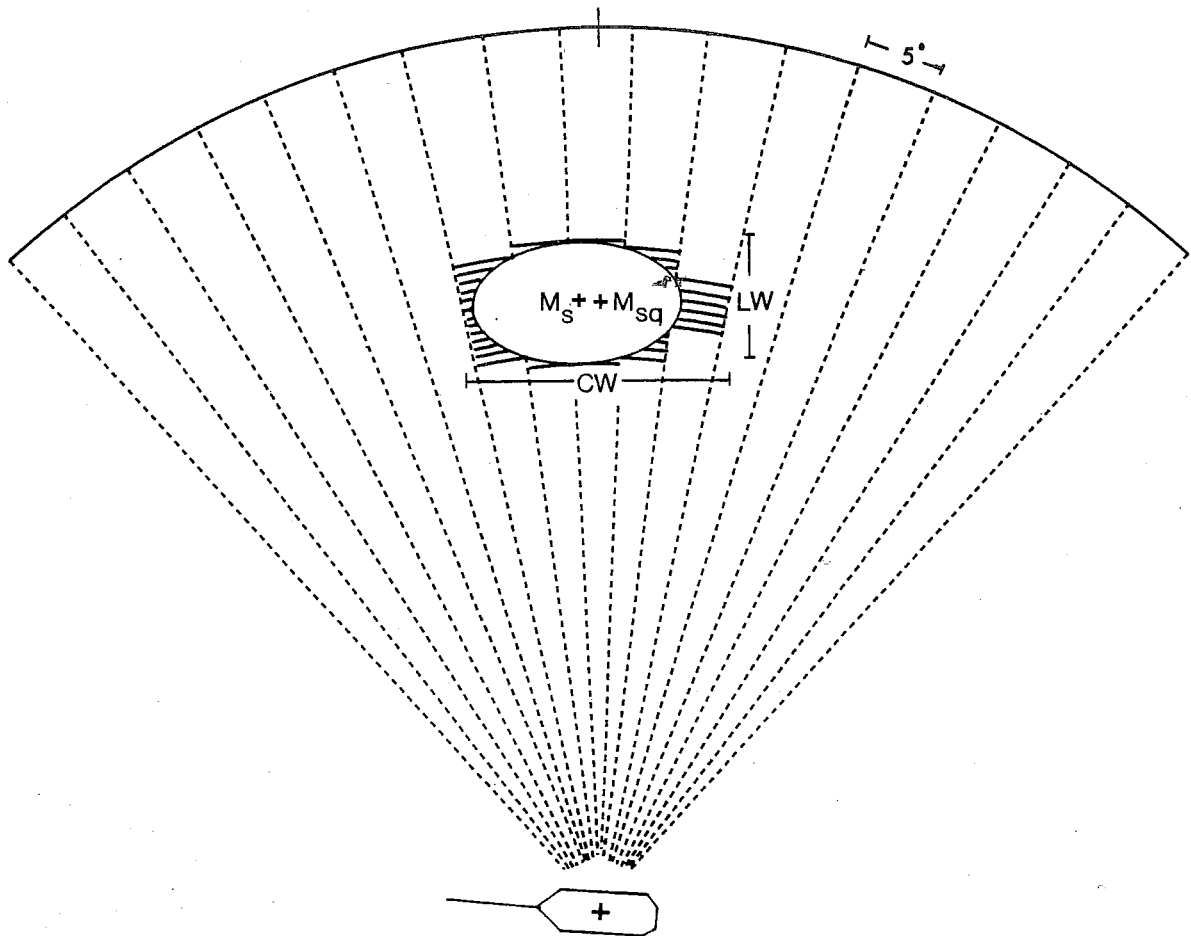


Figure 8. Sonar distortion of an elliptical school. The hachure shows the outer edges of the projected school area (CW: crosswise extent, LW: lengthwise extent,  $M_{sq}$ : midpoint of square enveloping the projected school area,  $M_s$ : real midpoint of the school).

The schooling in darkness of spawning, migrating herring is in agreement with other observations of herring in this stage of the life history (Harden Jones, 1962; Devold, 1969). The herring may maintain the schooling by sensing their neighbours through lateral line receptors when the light intensity is below the limit for visual sensing (Partridge and Pitcher, 1980).

#### Swimming behaviour

Average horizontal swimming speeds of schools, both those encircled and those passed over, were all within the ranges in the laboratory or ahead of trawls (Blaxter, 1969). The faster swimming speed of schools passed over may have been caused by errors in positioning of the schools, or by intensive avoidance reactions to the approaching vessel. There was a distinct variation in the swimming speed, both from one observation interval to another and between schools. The former may be caused by random measurement errors or the internal

dynamics of the schools (Van Olst and Hunter, 1970), the latter by differences in the level of activity between schools. Some schools tended to swim straight ahead, while others tended to move in circles, indicating differences in avoidance behaviour caused by other stimuli than the vessel.

Maximum swimming speeds of up to 17 body lengths/s are far above the 10 body lengths/s predicted from the muscle contraction time (Wardle, 1975) or observed in the laboratory or ahead of trawls (Blaxter, 1969). The measurements may be affected by random positioning errors, but they are in accordance with recordings of up to 16 body lengths/s of 30-cm-long river herring (Dow, 1962).

#### Vessel avoidance

The schools avoided the vessel horizontally in about 70% of cases. In particular, the night recordings in the Nordmøre fjords and off Nordland provide support for

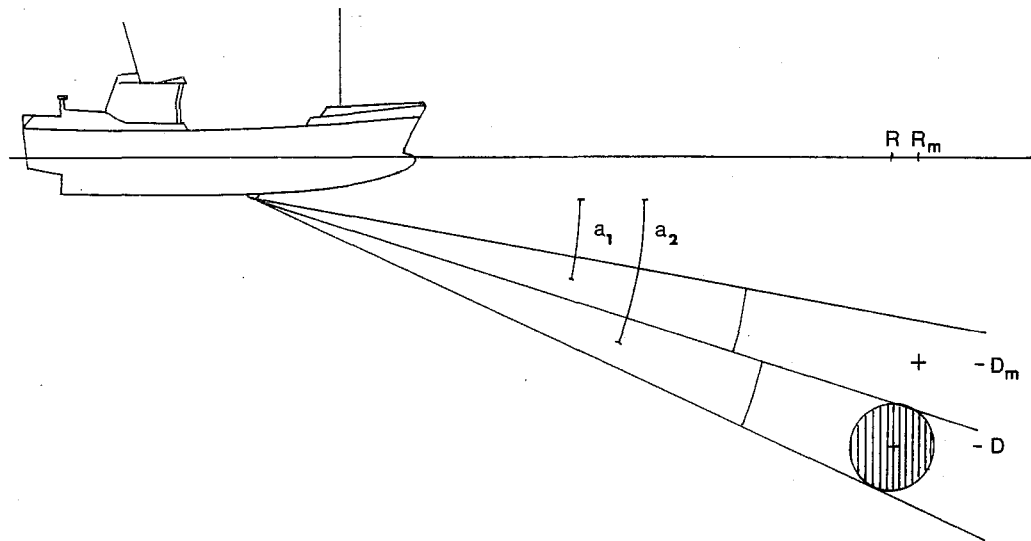


Figure 9. Sonar measurement of the midpoint of a circle-shaped school ( $R, D$ : correct horizontal distance and depth measured by tilt angle  $a_2$ .  $R_m, D_m$ : horizontal distance and depth measured by tilt angle  $a_1$ ).

the argument that avoidance is based on the response to sound generated by the vessel. The partial guiding of the schools by both methods of manoeuvring, and the diving of the schools as the vessel passed over, indicate that the herring are sensitive to and avoid increasing sound pressure gradients as expressed in the emission pattern of vessel-generated sound (Urick, 1983). A clear decrease in horizontal avoidance with increasing direction of bearing shows that herring cease avoidance behaviour when the gradients decrease. Similar guidance has been demonstrated by use of a discrete, low-frequency sound source directed towards a herring school (Dalen, 1973), and the average diving speed as the vessel passed over of 0.47 m/s is close to Doppler-shift measurements of the diving speed of herring in similar situations (Olsen *et al.*, 1983b). However, the diving speeds as the vessel passed over may be wrong because of the uncertainty in recording school depth by sonar as opposed to echo sounder.

There were no clear connections between horizontal avoidance and vessel-to-school distance, vertical avoidance and school depth, or avoidance behaviour and speed of the vessel as predicted by the avoidance model (Olsen *et al.*, 1983a). There were, however, few measurements close to the vessel, and increased avoidance has earlier been observed only within 50 m of the vessel (Olsen *et al.*, 1983b; Ona and Chruickshank, 1986).

The schools off Nordland were probably on a spawning migration, and avoided horizontally at about twice the speed of the schools on any other grounds and dived as the vessel steamed towards them, which suggests that herring at this stage of life history are especially sensitive (see also Mohr, 1969).

### Purse-seine avoidance

Norwegian spring-spawning herring showed no purse-seine avoidance at night, probably because vision is of major importance in organized behaviour towards moving fishing gear (Wardle, 1986). On the North Sea grounds, however, herring schools occasionally avoided the purse seine in daylight, in some cases by just swimming out under the sinking net. On other occasions the schools escaped under the vessel. This behaviour seemed to occur as the leadline started to rise, and the schools were probably herded out by the gear in the same way as in front of trawls (Mohr, 1969; Wardle, 1986). The visual stimuli from the gear seem to have a stronger effect than the sound stimuli from the vessel.

The dramatic rise and panic-swimming at the sea surface of the schools which were caught on the Egersundbank resembles a "flash-expansion" to escape a predator (Pitcher, 1979). The behaviour was probably triggered by preying saithe present in the locality or by the sight of the gear. There were numerous dead herring in the net, probably because of lethal concentrations of metabolites from anaerobic metabolism during burst speeds (Blaxter, 1969). The preying cod in the catches of Norwegian spring-spawning herring did not trigger similar behaviour, probably because cod is a stalking, twilight predator of herring (Pitcher and Turner, 1986).

The behaviour towards the purse seine explains why the catch success was about 90 % during the night-time winter fishery for Norwegian spring-spawning herring, and only 64 % during the daylight summer fishery for North Sea herring. Similar day and night differences are reported for Pacific tuna during purse seining (Scott and Flittner, 1972).

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## References

- Anon. 1974. UNDP/FAO Pelagic fishery project (IND/169/539). Progress report no. 8, *Cochin/Bergen*, Norway.
- Anon. 1975. UNDP/FAO Pelagic fishery project (IND/169/539). Technical report no. 9. Results of the 1974 aerial survey, *Cochin/Bergen*, Norway.
- Blaxter, J. H. S. 1969. Swimming speeds of fish. *Fish. Rep.*, 62: 69-100.
- Blaxter, J. H. S. 1985. The herring: a successful species? *Can. J. Fish. aquat. Sci.*, 42: 21-30.
- Blaxter, J. H. S., Gray, J. A. B., and Denton, E. J. 1981. Sound and startle responses in herring shoals. *J. Mar. Biol. Assoc. U.K.*, 61: 871-869.
- Bodholt, H. 1982. A multi-beam sonar for fish school observation. ICES/FAO Symposium on Fisheries Acoustics, Bergen, Norway, 21-24 June 1982, Doc. no. 55.
- Bolster, G. C. 1958. On the shape of herring schools. *J. Cons. perm. int. Explor. Mer.*, 23: 228-234.
- Breder, C. M. 1959. Studies on social groupings in fishes. *Bull. Am. Mus. Nat. Hist.*, 98: 1-28.
- Cushing, D. H. 1960. Fishing gear and fish behaviour. In *Proceedings of the World Scientific Meeting on the Biology of Sardines and Related Species*, Rome, 1959 (Methodological Paper 3), pp. 1307-1326. Ed. by H. Rosa, Jr. and G. Murphy. Rome.
- Dalen, J. 1973. Stimulering av sildestimer. (Stimulation of herring schools). 73-143-T, Inst. Techn. Cybern. Norwegian Technical Highschool. (Unpublished).
- Devold, F. 1969. The behaviour of the Norwegian tribe of the Atlanto-Scandian herring. *FAO Fish. Rep.*, 62: 534-549.
- Dow, R. L. 1962. Swimming speed of river herring *Pomolobus pseudoharengus*. *J. Cons. int. Explor. Mer.*, 27: 77-80.
- Freytag, G., and Karger, W. 1969. Investigations on noises caused by fishing vessels and their sources. ICES CM 1969/B:12.
- Gjestland, T. 1968. Undervanns støygenerering ved båter, støyens karakter og dens betydning for fangst og bruk av sonaranlegg. (Underwater noise generation by boats, noise characteristics and its importance for capture and use of sonar equipment). Thesis, Norw. Techn. Highschool. (Unpublished).
- Halvorsen, H. S. 1985. En evaluering av mulighetene for mengdemåling av pelagisk stimpfisk med horisontalt rettet sonar. (An evaluation of the possibilities for abundance estimation of pelagic schooling fish by horizontal guided sonar). Thesis, Univ. Bergen, Norway. (Unpublished).
- Harden Jones, F. R. 1962. Further observations of the movements of herring (*Clupea harengus* L.) shoals in relation to the tidal current. *J. Cons. perm. int. Explor. Mer.*, 27: 52-76.
- Misund, O. A. 1986. Sonarobservasjonar av stimåttferd under ringnotfisket etter sild. (Sonar observations of schooling behaviour during herring purse seining). Thesis, Univ. Bergen, Norway. (Unpublished).
- Mitson, R. B. 1983. Fisheries sonar (incorporating 'Underwater observation using sonar', by D. G. Tucker). Fishing News Books Ltd, Farnham, Surrey, England.
- Mohr, H. 1969. Observations on the Atlanto-Scandian herring with respect to schooling and reactions to fishing gear. *FAO Fish. Rep.*, 62: 567-577.
- Mohr, H. 1971. Behaviour patterns of different herring stocks in relation to ship and midwater trawl. In *Modern fishing gear of the world*, 3, pp. 368-371. Ed. by H. Kristjonsson. Fishing News Books Ltd, Farnham, Surrey, England.
- Olsen, K. 1969. Directional responses in herring to sound and noise stimuli. ICES CM 1969/B:20.
- Olsen, K. 1971. Influence of vessel noise on the behaviour of herring. In *Modern fishing gear of the world*, 3, pp. 291-294. Ed. by H. Kristjonsson. Fishing News Books Ltd, Farnham, Surrey, England.
- Olsen, K. 1976. Evidence for localization of sound by fish in schools. In *Sound reception in fish*, pp. 257-270. Ed. by A. Scuijf and A. D. Hawkins. Elsevier, Amsterdam.
- Olsen, K., Angell, J., and Løvik, A. 1983a. Quantitative estimation of the influence of fish behaviour on acoustically determined fish abundance. *FAO Fish. Rep.*, 300: 139-149.
- Olsen, K., Angell, J., Pettersen, F., and Løvik, A. 1983b. Observed fish reactions to a surveying vessel with special reference to herring, cod, capelin and polar cod. *FAO Fish. Rep.*, 300: 131-138.
- Ona, E., and Chruickshank, O. 1986. Haddock avoidance reactions during trawling. ICES CM 1986/B:36.
- Partridge, B. L., and Pitcher, T. J. 1980. The sensory basis of fish schools, relative roles of lateral line and vision. *J. comp. Physiol.*, 135: 315-325.
- Partridge, B. L., Pitcher, T. J., Cullen, M. J., and Wilson, J. 1980. The three-dimensional structure of fish schools. *Behav. Ecol. Sociobiol.*, 6: 277-288.
- Pitcher, T. J. 1979. The role of schooling in fish capture. ICES CM 1979/B:5.
- Pitcher, T. J. 1983. Heuristic definitions of shoaling behaviour. *Anim. Behav.*, 31: 611-613.
- Pitcher, T. J., and Partridge, B. L. 1979. Fish school density and volume. *Mar. Biol.*, 54: 383-394.
- Pitcher, T. J., and Turner, J. R. 1986. Danger at dawn: experimental support for the twilight hypothesis in shoaling minnows. *J. Fish. Biol.*, 29: 59-70.
- Radakov, D. V. 1973. Schooling in the ecology of fish. Israel Program for Scientific Translations Ltd. Distributed in Europe by John Wiley & Sons Ltd, Chichester, England.
- Schwarz, A. L., and Geer, G. L. 1984. Response of Pacific herring, *Clupea harengus pallasi*, to some underwater sounds. *Can. J. Fish. aquat. Sci.*, 41: 1183-1192.
- Scott, J. M., and Flittner, G. A. 1972. Behaviour of bluefin tuna schools in the eastern North Pacific Ocean as inferred from fishermen's logbooks, 1960-67. *Fish. Bull., U.S.*, 70: 915-927.
- Smith, P. E. 1977. The effects of internal waves on fish school mapping with sonar in the California Current area. *Rapp. P.-v. Réun. Cons. int. Explor. Mer.*, 170: 223-231.
- Squire, J. L., Jr. 1978. Northern anchovy school shapes as related to problems in school size estimation. *Fish. Bull., NMFS/NOAA*, 76(2): 443-448.
- Urick, R. J. 1983. *Principles of underwater sound for engineers*. McGraw-Hill, New York.
- Van Olst, J. C., and Hunter, J. R. 1970. Some aspects of the organization of fish schools. *J. Fish. Res. Bd Can.*, 27: 1225-1238.
- von Brandt, A. 1984. *Fish catching methods of the world*. Fishing News Books Ltd, Farnham, Surrey, England. 432 pp.
- Wardle, C. S. 1975. Limits of fish swimming speed. *Nature, Lond.*, 225: 725-727.
- Wardle, C. S. 1986. Fish behaviour and fishing gear. In *The behaviour of teleost fishes*, pp. 463-495. Ed. by T. J. Pitcher. Croom Helm, London and Sydney.
- Wilkins, M. E. 1986. Development and evaluation of methodologies for assessing and monitoring the abundance of widow rockfish *Sebastes entomelas*. *Fish. Bull., U.S.*, 84: 287-310.
- Zar, J. H. 1974. *Biostatistical analysis*. Prentice-Hall Inc., Englewood Cliffs, New Jersey, USA.