Hydroacoustic Signal Classification of Fish Schools by Species[1,2]

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Features extracted from hydroacoustic backscatter from fish schools enabled classification by species. Target species were cod (*Gadus morhua*), capelin (*Mallotus villosus*), and mackerel (*Scomber scombrus*), observed in the northern Gulf of St. Lawrence during 1985–86. Two features of internal school density (20 log *R* amplification) were the best discriminators. These were mean standardized peak to trough distance (SPT) and mean distance between voltage peaks (PP). Quadratic discriminant functions based on the variables SPT, PP, an inverse coefficient of variation, school depth, and off-bottom distance correctly classified 93% of schools (1986). These functions also correctly classified 93% of cod and capelin schools acoustically sampled independently during 1985. The target strength of individual fish was a less successful discriminator of species. For cod and capelin of known length, average target strength (TS) was a linear function of length: TS (decibels) = $-65 + 20 \log_{10}$ length (centimetres). Mackerel had target strengths that were 8–12 dB less than those of cod of equivalent length. Quadratic discriminant functions based on target strength, school depth, and off-bottom distance correctly classified 77% of schools by species. Our methods are generalized to any schooling species or environment.

Certaines caractéristiques des échos hydroacoustiques en provenance de bancs de poissons ont permis d'en préciser l'espèce. Les espèces visées, la morue (*Gadus morhua*), le capelan (*Mallotus villosus*) et le maquereau (*Scomber scombrus*), avaient été étudiées dans la partie nord du golfe du Saint-Laurent en 1985–1986. Les meilleurs discriminateurs étaient représentés par deux caractéristiques de la densité interne des bancs (amplification de 20 log *R*). Il s'agissait de la distance moyenne normalisée entre les pics et les creux (PCN) et la distance moyenne entre les pics de tension (PT). Des fonctions de discriminants quadratiques basées sur les variables PCN, PT, un coefficient inverse de variation, la profondeur du banc et la distance à partir du fond, ont permis de déterminer correctement l'espèce de 93 % des bancs (1986). Ces fonctions ont aussi permis de déterminer correctement à 93 % l'espèce de bancs de morue et de capelan ayant fait l'objet d'un relevé acoustique indépendant en 1985. La force de l'écho des poissons individuels s'est avérée être un discriminant de l'espèce moins efficace. Dans le cas de morues et de capelans de longueur connue, la force moyenne de l'écho (FE) était une fonction linéaire de la longueur : FE (decibels) = $-65 + 20 \log_{10}$ longueur (centimètres). La force de l'écho réfléchie par les maquereaux était inférieure de 8 à 12 dB à celle des morues de longueur équivalente. Les fonctions à discriminants quadratiques basées sur la force de l'écho, la profondeur du banc et la distance du fond ont permis de déterminer correctement à 77 % l'espèce de poisson des bancs. Les auteurs ont généralisé leurs méthodes à l'ensemble des espèces formant des bancs et des environnements.

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The application of hydroacoustic assessment techniques has been limited by an inability to objectively discriminate among taxonomic groups of sound scatterers (Thorne 1983). To date, most workers have used identification methods based on net sampling near the acoustic transect and on visual interpretation of echograms. In many instances, however, neither of these techniques has enabled objective taxonomic discrimination.

Taxonomic compositions of acoustically determined biomasses are often assigned by reference to the composition of net samples taken near the acoustic transect. There are two central problems with this approach. First, net samples seldom reflect actual species or size composition; second, net samples in practice cannot achieve spatial or temporal sampling which is comparable with that of acoustic sampling (R. E. Thorne. "Hydroacoustics and ground truth." ICES/FAO International Symposium on Hydroacoustics, Seattle, WA, June 22–26, 1987). In single-species environments or where schools are large, widely separated, and have a high catchability, these biases of net sampling may be small. In multispecies environments, especially where schools are small, interspersed, and have a low or varying catchability, net sampling is often unworkable even as a rough means of taxonomic identification.

Visual interpretations of echograms, with taxonomic discrimination based on "rules of thumb," represent the first attempts to use the acoustic signal itself to identify targets by taxa. Such methods are used by many commercial fishermen. The "rules of thumb" pertain to multivariate assessments of voltage strength (evident as shades of grey on an echogram)

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[2]A similar paper entitled "Classification of acoustic images of fish schools by species" was presented to the ICES/FAO International Symposium on Fisheries Acoustics, Seattle, WA, June 22–26, 1987.

and school shape, size, and position in the water column, generally mediated by knowledge of the species likely to be encountered. These techniques suffer from subjectivity and are labor intensive.

Several attempts have been made to quantify, make more objective, and automate echogram interpretation by measuring various characteristics and using these as input to pattern recognition algorithms (Azzali 1982; Nion and Castaldo 1982). These techniques, although an improvement over subjective visual estimates, have a major weakness. Echograms are simply rough graphic representations of amplified acoustic backscattered energy and present a smoothed picture of any higher frequency information contained in the signal. Echogram interpretation therefore is inherently wasteful of information that may assist taxonomic classification.

Several recent approaches use information present in the digitized backscattered signal itself to classify targets. These approaches are of three major types: (1) dual-beam and split-beam techniques for sizing sound scatterers, (2) wideband multifrequency response techniques, and (3) feature extraction from narrowbeam echosounder signals.

Dual-beam and split-beam techniques have shown potential for separating organisms of different sizes (Traynor and Ehrenberg 1979; Dickie et al. 1983; Burczynski and Johnson 1986; Foote et al. 1986). These techniques are constrained, however, by their power to resolve single targets. Many species school at densities sufficiently high to make resolution of single targets problematic (Dickie et al. 1983). An additional limitation is that size classification enables taxonomic classification only when target taxa have discrete size distributions.

Other workers have used complex wideband and multiple-frequency echosounders to characterize responses of targets of various sizes and taxa to a range of frequencies. These techniques are based on the theoretical frequency dependence of the relationship between target size and backscattering strength (Holliday 1972). Multifrequency response techniques have been used in attempts to separate fish from plankton (Saetersdal et al. 1984) and to classify fish by species (Zakharia and Sessarego 1982; E. J. Simmonds and F. Armstrong. "A wide band echosounder: measurements on cod, saithe, herring, and mackerel from 27 to 54 kHz." ICES/FAO International Symposium on Fisheries Acoustics, Seattle, WA, June 22–26, 1987).

A technically simpler empirical approach employing narrowband echosounders has been to characterize and then recognize the patterns of backscatter from organisms or groups of organisms of specific types (Deuser et al. 1979; Giryn et al. 1979; D. Vray, G. Gimenez, and R. Person. "Attempt of classification of echosounder signals based on the linear discriminant function of Fisher." ICES/FAO International Symposium on Fisheries Acoustics, Seattle, WA, June 22–26, 1987). These authors used variations of Fourier transformations of the signal to classify targets. To date, however, these potentially powerful approaches to signal classification and recognition have yielded limited success.

In our approach to target identification, we hypothesized that the acoustic signal from schools of fish should contain information sufficient to enable discrimination by species. Two types of characterization were investigated: (1) target strengths of individual fish and (2) features of the backscattered energy and density structure of whole schools. We tested these concepts using acoustic signals from free-ranging schools of cod (*Gadus morhua*), capelin (*Mallotus villosus*), and mackerel (*Scomber scombrus*).

Target strength is length dependent in fishes with swim bladders (Midttun 1984). In our study these are represented by cod and capelin. Fishes without swim bladders, such as mackerel, have target strengths well below those of much smaller fishes with swim bladders (Nakken and Olsen 1977; Foote 1980; Edwards and Armstrong 1983). We thus hypothesized that target strengths of individual fish from schools of cod would be greater than those from schools of capelin, which in turn would be greater than those from schools of mackerel.

The acoustic backscattered energy from a fish school, after correction for spreading and attenuation losses (amplification $20 \log R + 2\alpha R$; where R = range and α = attenuation coefficient of sound in water), is proportional to the density of the school (MacLennan and Forbes 1984). An acoustic backscatter profile can thus be made analogous to a vertical section of school density. We hypothesized that three types of characteristics of the school density profile would be species dependent and thus allow classification: (1) position in water column, (2) external shape and size, and (3) internal density structure.

In this paper, we present the results of these investigations, develop specific acoustic criteria for discriminating among schools of cod, capelin, and mackerel, and discuss the general implications of our findings to the taxonomic classification of acoustic signals.

Methods

This study was carried out at Brador Bay, Quebec, Canada, on the north shore of the Gulf of St. Lawrence. Dockside measurements were made at an abandoned deepwater schooner wharf at Bassin Ile within Brador Bay.

To establish a fish size–target strength relationship, immobilized cod and mackerel and free-swimming capelin of known length were ensonified at dockside. Cod and mackerel were caught by hand line in shallow water (< 25 m). Fish that were obviously injured or overly traumatized were released. Healthy fish were transported to dockside in a live box. Unfortunately, mackerel expired quickly. At dockside the transducer was fixed over 10 m of water. Twenty five cod of fork lengths 27–122 cm and five mackerel of fork lengths 36–43 cm were measured for target strength. Fish were suspended at a distance of 4–8 m from the transducer, in its far field, from monofilament line tied through punctures made in the dorsal fin and behind the head. Mackerel required the attachment of a weighted line to their ventral surface to keep them in dorsal aspect. SCUBA divers and line handlers at the surface attempted to keep the whole fish within the beam, with their long axis parallel to the transducer face, during measurement. As the basal diameter of the half-power ensonified cone of the narrow beam ranged from approximately 0.7 m at 4 m from the transducer to 1.4 m at 8 m from the transducer, the larger cod just fit into the beam. Cod were docile during this procedure; mackerel were dead when measured. Several hundred pings were recorded from each fish. On four occasions during the above work, capelin schools were ensonified in dorsal aspect as they swam freely beneath the transducer. The lengths of these fish were determined visually at close range by SCUBA divers.

We used a Biosonics model 105 echosounder (120 kHz), fitted with a dual-beam transducer (10 and 25°) mounted in a V-fin towing body, to make all acoustic measurements. Pulses of 0.8 ms duration were generated at a rate of $5 \cdot s^{-1}$. A Biosonics tape recorder interface and Sony video recording system stored all data for analysis. When working at sea, the transducer was towed beside the 9-m vessel at a depth of approximately 2 m. Transducer stability was enhanced by a series of movement-damping springs which isolated the movements of the boat from that of the towed body. Boat speed was approximately 10 $km \cdot h^{-1}$. Under these conditions, noise peaks at 80 m of depth were approximately 20 mV with 20 log *R* amplification and 50 and 100 mV on the narrow and wide beams, respectively, with 40 log *R* amplification. Field calibration carried out on a 5.08-cm-diameter stainless steel ball bearing indicated that its target strength was a stationary time series (constant mean and variance) with SE of 0.3 dB.

A total of 46 schools of capelin, 70 schools of cod, and 11 schools of mackerel were positively identified during the summers of 1985 and 1986. Cod and mackerel schools were considered positively identified if, after acoustic sampling, a multihooked jig line lowered into the school hooked a single species on three successive attempts. Jig lines were guided into the school by reference to the echogram. Capelin schools were considered positively identified when observed visually from the surface or by SCUBA divers. Capelin identified from the surface were also subjected to the jig line test, and in all cases, nothing was hooked. Attempts were made to sample schools of varying sizes and at varying depths from the surface to approximately 50 m. A few cod schools were positively identified at greater depths. During 1985, acoustic data were recorded from only the narrow beam (thus, no target strengths are reported). Data collected during 1986 were integrated in real time with a Biosonics model 121 digital echo integrator. In 1986, both narrow- and wide-beam signals were also recorded on tape with 40 log *R* amplification, to be subjected later to target strength analysis.

Target strengths were determined with a Biosonics model 181 dual-beam processor following methods given by Traynor and Ehrenberg (1979). Echoes were classified as single fish if the peak signal on the narrow beam was greater than 100 mV and half height (−6 dB) width was between 0.55 and 1.1 ms. A −18 dB echo width criteria was not used because its use reduced sample size considerably. Target strengths calculated using the −6 dB criterion and those calculated using both the −6 dB criterion and a −18 dB maximum width of 2 ms were significantly correlated ($r = 0.80$). The slope of this relationship (0.88) was not significantly different from 1 ($P > 0.05$).

To analyze school characteristics, voltages made proportional to density ($V^2 \propto$ density; 20 log *R* amplification (Burczynski 1982)) were digitized at a frequency of 16.5 kHz on a TECMAR Labmaster A/D converter and then stored on computer disc. For each school, two randomly selected sequences of four or five consecutive echosounder pings were recorded. Schools were delimited by the occurrences of voltages of less than 100 mV for a duration of 3.0 ms (2.25 m). A computer program was used to calculate the following criteria for each sample: (1) off-bottom distance (metres), (2) depth of school (metres), (3) mean squared voltage, (4) standard deviation of squared voltage, (5) maximum squared voltage, (6) mean distance between within school voltage peaks (metres) (hereafter called PP), and (7) mean peak to trough squared voltage standardized to the mean squared voltage (hereafter called SPT) (Fig. 1). Peaks and troughs were defined as having higher and lower voltages, respectively, than the two preceding and two following voltages.

Discriminant analysis was used to characterize and classify schools by species. To determine the variables to be entered into the discriminant analyses, variables identified in the preceding paragraph (20 log *R*) were subjected to stepwise selection. From the 40 log *R* signal, the following variables were entered: target strength (TS), school depth, and off-bottom distance. We attempted to use variables that were robust against variability in amplifier gain settings and system calibration. Thus, an inverse coefficient of variation (mean/standard deviation) (hereafter called CV) was used instead of standard deviation. Prior to entry into discriminant analyses, variables whose distributions suggested non-normality (PP, school depth, and off-bottom distance) were subject to $\log_e + 1$ transformation (Shapiro–Wilk statistic, $P > 0.01$). Covariance matrices were tested for homogeneity (Morrison 1976). If a chi-square test indicated that the covariance matrices of the three species were not homogeneous, the use of a pooled covariance matrix and linear discriminant functions was rejected in favor of quadratic discriminant functions based on within-group matrices (Morrison 1976). Quadratic discriminant functions can be expressed as

$$f(x_1,\ldots,x_n) = a_{11}x_1^2 + \ldots + a_{nn}x_n^2 + 2a_{12}x_1x_2 + \ldots + 2a_{1n}x_1x_n + \ldots + 2a_{n-1,n}x_{n-1}x_n$$

where $x_1,\ldots,x_n$ are the values of the measured criteria and $a_{11},\ldots,a_{nn}$ are the coefficients of the quadratic function. Discriminant analyses were carried out on the programs of SAS and SAS/STAT for personal computers (SAS Institute Inc. 1985). Differences were considered significant if $P < 0.05$ unless stated otherwise.

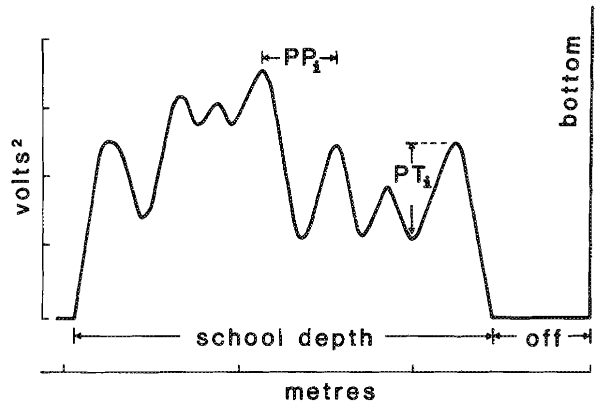

FIG. 1. Measurement of school descriptors. Time measures (school depth, off-bottom distance, PP) calculated in *m* from initial measure (ms). PP = $\Sigma_1^n PT_i \cdot n^{-1}$). Voltage measures (maximum, mean, SD, and peak to trough distance (PT) in V^2. SPT is the unitless quantity SPT = $\Sigma_1^n PT_i \cdot n^{-1} \cdot (V^{-2})$.

Results

Target Strength

The mean target strengths of cod measured at dockside showed a positive linear relationship to fish length (TS (decibels) = −67.5 + 21 $\log_{10}$ length (centimetres) ($n = 25$, $r = 0.95$, SE = 1.0 dB) (Fig. 2). Capelin schools ensonified at dockside had a mean length of 16.5 cm and a mean target strength of −41.0 dB (SD = 1.19) (Fig. 2). The cod length – target strength regression, extrapolated to 16.5 cm, predicted a mean target strength of −41.9, which did not differ significantly from the value measured for capelin.

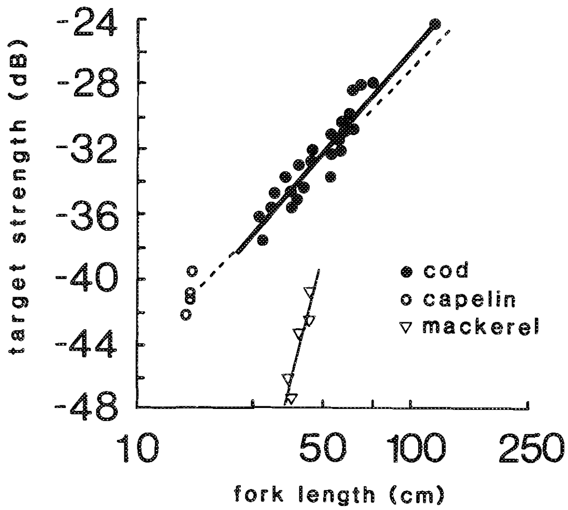

FIG. 2. Dorsal aspect target strengths of cod, capelin, and mackerel measured at dockside at Brador Bay, Canada, during 1986. Cod and mackerel were tethered during measurement; capelin were free swimming. Cod and capelin together yield the regression TS(dB) = $-65 + 20 \log_{10}$ length (cm) ($n = 29$, $r = 0.97$, SE = 1.0 dB). Mackerel yield the regression TS(dB) = $-151 + 67 \log_{10}$ length (cm) ($n = 5$, $r = 0.92$, SE = 1.0 dB).

The mean target strength of mackerel was also a linear function of the length of the fish: TS(decibels) = $-151.3 + 67 \log_{10}$ length (centimetres) ($n = 5$, $r = 0.92$, SE = 1.0 dB). This relationship was orders of magnitude different from the equivalent regression for cod. Mackerel target strength averaged −44.0 dB and was 8–12 dB less than the target strength of cod of equivalent length. Mackerel with lengths of approximately 40 cm had target strengths similar to those of 16.5-cm capelin (approximately −42 dB).

Mean target strengths measured at sea were −31.4 dB for cod ($n = 1576$), −41.8 dB for capelin ($n = 1681$), and −42.7 dB for mackerel ($n = 42$) (Fig. 3). Capelin and mackerel target strengths were normally distributed around their means. Cod target strength had a bimodal distribution, with modes at −26 and −50 dB. The mean target strength of cod was greater than the mean target strengths of capelin and mackerel (Mann–Whitney test, $P < 0.05$). Capelin and mackerel target strengths did not differ (Mann–Whitney test, $P > 0.05$). All three species exhibited a wide range of target strength.

Target strengths were determined for 55 of 60 cod, capelin, and mackerel schools measured at sea (Fig. 4). No single targets could be resolved from the five schools (four mackerel and one capelin) for which no target strength is reported. For many schools the number of single targets assessed was low (in six cases, $n = 2$). The modal frequencies of the mean target strength of cod and capelin schools were 14 dB apart. The mean target strength of the seven mackerel schools ranged from −30 to −48 dB, with a modal frequency similar to that of capelin.

Stepwise discriminant analysis selected all three variables entered as discriminators of species in the order target strength, school depth, and off-bottom distance. Quadratic discriminant functions were calculated because covariance matrices were heterogenous ($X^2 = 103$, $df = 12$, $P < 0.001$) (Table 1). These functions correctly classified 77% of schools measured during 1986 (or 84% if only those schools with estimated target strength are included). Classification success was unequal among species. For cod, classification was 100% correct

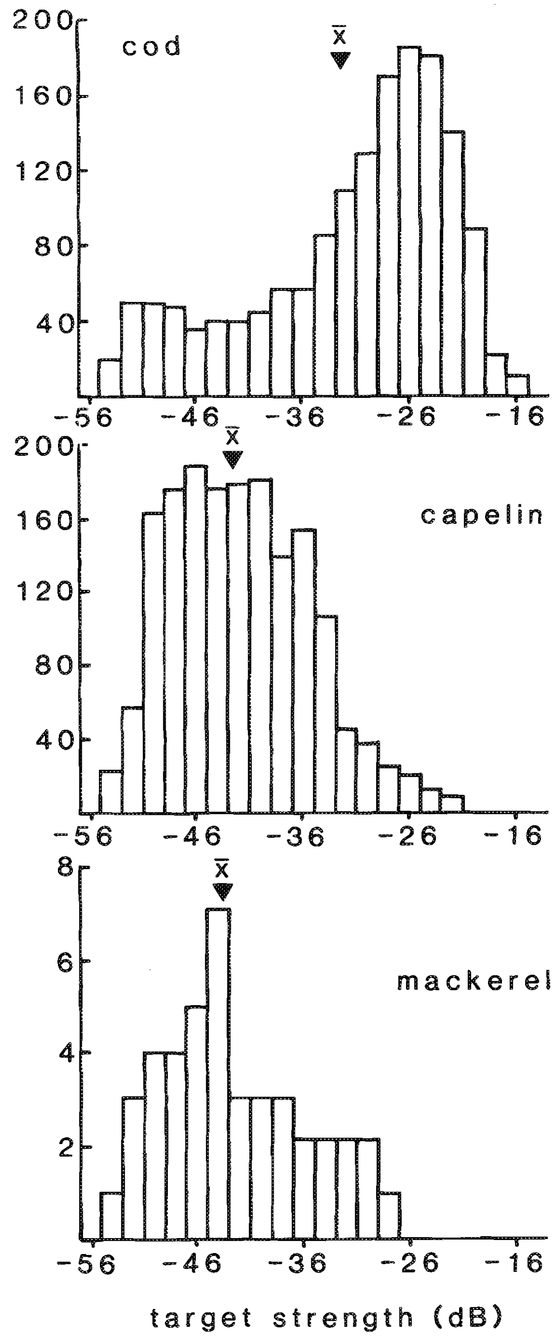

FIG. 3. Target strengths of cod, capelin, and mackerel measured at sea at Brador Bay, Canada, during 1986. Mean ± SD (n): cod, -31.4 ± 9.4 (1576); capelin, -41.8 ± 6.6 (1681); mackerel, -42.7 ± 6.8 (42).

whereas for capelin and mackerel, only 61 and 55% of schools, respectively, were classified correctly.

Density Signal

The PP and SPT densities both differed significantly among the three species (Table 2). Vertical density profiles of capelin schools were characterized by low values of SPT and PP (Fig. 5). By contrast, mackerel schools had high values of SPT and intermediate values of PP. Cod schools were characterized by intermediate values of SPT and high values of PP. No other measured criteria differed significantly among all three species, although capelin schools were greater than both cod and mack-

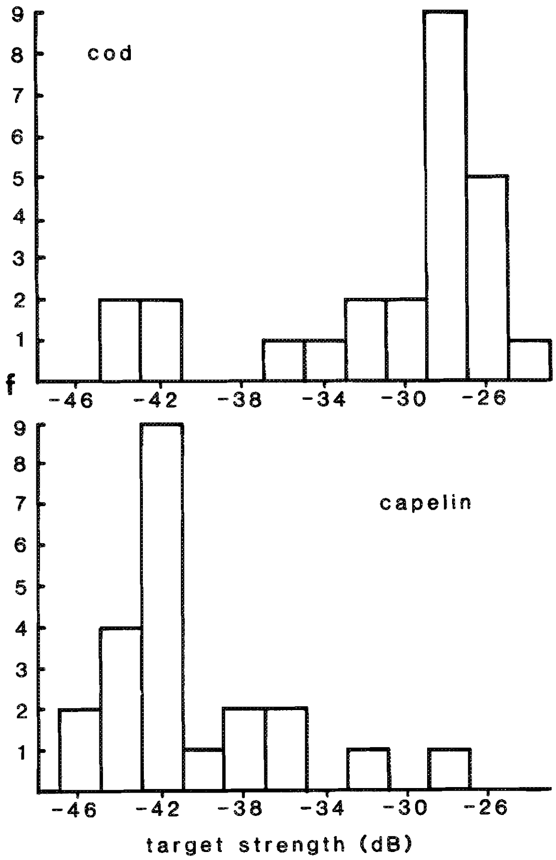

FIG. 4. Mean target strengths of schools of cod and capelin measured at sea at Brador Bay, Canada, during 1986.

TABLE 1. Discriminant analysis classification by target strength, school depth, and off-bottom distance of 23 capelin, 26 cod, and 11 mackerel schools measured in 1986. "No class" indicates schools for which all variables were not available (i.e. TS, n = 0). Percentages in parentheses.

	Classified into species				
From	Capelin	Cod	Mackerel	No class	Total
Capelin	14(61)	5(22)	3(13)	1(4)	23(38)
Cod	0(0)	26(100)	0(0)	0(0)	26(43)
Mackerel	0(0)	1(9)	6(55)	4(36)	11(18)
Total	14(23)	32(53)	9(15)	5(8)	60(100)

TABLE 2. Mean untransformed values of descriptors of capelin, cod, and mackerel schools measured during 1986 (n in parentheses). Underlined values form nonsignificantly different groups (Duncan's multiple range test, $P < 0.05$). For off bottom, school depth, and PP, statistical comparisons based on $\log_e + 1$ transformations.

	Cod(26)	Mackerel(11)	Capelin(23)
Off bottom (m)	0.52	1.96	4.60
School depth (m)	4.29	2.53	13.02
Maximum voltage (V^2)	2.7	0.8	20.0
Mean voltage (V^2)	0.58	0.11	2.30
SD of voltage (V^2)	0.72	0.19	4.16
PP (m)	0.87	0.65	0.75
SPT	2.04	3.51	1.55

erel in school depth and mean, maximum, and total relative density. Although mean off-bottom distance did not differ among species, cod tended to be associated most closely with the bottom and capelin were the most pelagic.

Stepwise discriminant analysis selected species discriminators in the following order: SPT, PP, school depth, CV, and off-bottom distance. Quadratic discriminant functions were calculated because covariance matrices were heterogenous (X^2 = 186, df = 30, $P < 0.001$) (Table 3). These functions classified correctly 93% of all schools measured in 1986 and from which the functions were derived (Table 4). All species were classified with good success (>90% correct).

The quadratic discriminant functions generated from the 1986 data correctly classified 93% (62 of 67) of cod and capelin schools ensonified during 1985 and for which the discriminating criteria were calculated (Table 5).

A stepwise discriminant analysis, which included all of the density signal variables indicated above plus target strength, selected target strength after SPT and PP, but removed target strength as a discriminator after the entry of the CV. The final selection of variables was the same as indicated above for the density signal.

Discussion

Target Strength

The fish length–target strength relationship reported here for cod is very similar to that published previously for cod at 120 kHz by Nakken and Olsen (1977). It is also in general agreement with summaries of length–target strength relationships for this species (Midttun 1984; Foote 1987). Mean target strength of capelin schools of known average length did not differ from that predicted by the regression of target strength on length for cod, suggesting that capelin and cod may be described by a single regression. Combining the data for cod and capelin yields the regression TS (decibels) = $-64.9 + 20 \log_{10}$ length (centimetres) (n = 29, r = 0.97, SE = 1.0 dB).

Our data support the existence of a linear relationship between length and mean target strength for mackerel, but suggest that this line is on average 10 dB lower, and has a steeper slope, than the regression for cod and capelin. These findings are consistent with previous comparisons of the target strengths of fishes having swim bladders with those that do not (Foote 1980; Edwards and Armstrong 1983). Nakken and Olsen (1977) did not report a length–target strength regression for mackerel, but target strengths reported for mackerel were 10–11 dB less than for cod of similar size. The mean mackerel target strength we determined at sea (−42.7 dB; SE = 1.0) did not differ significantly from that reported by Nakken and Olsen (1977) for mackerel of length 29–34 cm (−41.9 dB; SE = 1.0). The mean target strength relationship we developed for dead mackerel of known length, however, appears to predict somewhat lower values than reported by these authors.

The hypothesis that the mean target strength would differ among schools of cod, capelin, and mackerel, and thus allow classification of these species, was rejected. Our data suggest that there are two reasons for this result. First, as the measurements on fish of known length show, the target strengths of larger mackerel are similar to those of capelin; hence, target strength cannot be expected to be a good discriminator of these species. Second, schooling behavior may create fish densities at which the selection of single fish echoes becomes a highly

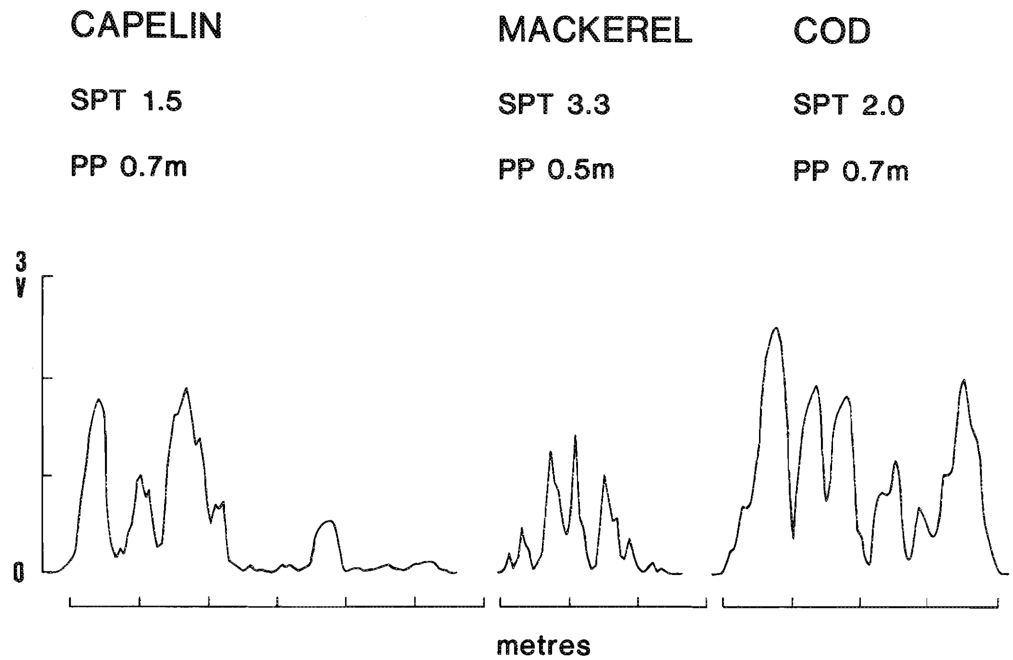

FIG. 5. Acoustic backscatter with 20 log R amplification which is proportional to vertical density sections through schools of capelin, mackerel, and cod of approximately equal maximum density. Signal patterns and values of SPT and PP indicated were typical of these species at Brador Bay during 1985 and 1986.

TABLE 3. Quadratic discriminant function coefficients generated from 23 capelin, 26 cod, and 11 mackerel schools measured during 1986. Variables are SPT, $\log_e$ (PP + 1) = PP, CV, $\log_e$ (school depth + 1) = SD, and $\log_e$ (off-bottom + 1) = OFF. Classification is to species with maximum value of D = constant + d_1 (SPT²) + ... + d_1 (CV²) + ... + 2d_1 (SPT) (PP) + ... + 2d_1 (OFF) (CV). For details see Methods.

	Capelin	Cod	Mackerel
Constant	−350.489	−297.405	−185.910
SPT	−43.207	−8.189	−3.367
PP	−492.337	−146.540	−254.749
SD	−2.127	−19.786	−22.184
OFF	−0.790	−44.229	−7.911
CV	−54.055	−31.729	−150.949
SPT·PP	−17.508	−9.134	13.285
SPT·SD	−2.338	−8.063	−3.811
SPT·OFF	1.790	5.199	−2.033
SPT·CV	4.691	−3.705	−1.734
PP·SD	−14.666	−21.044	3.621
PP·OFF	0.780	3.692	20.428
PP·CV	20.198	−7.779	−54.933
SD·OFF	0.156	4.694	7.477
SD·CV	−3.427	−5.752	−6.317
OFF·CV	−2.194	−4.193	1.792

TABLE 4. Quadratic discriminant analysis classification, by SPT, PP, coefficient of variation, school depth, and off-bottom distance, of 23 capelin, 26 cod, and 11 mackerel schools measured in 1986. Details of discriminant functions given in Table 3. Percentages in parentheses.

	Classified into species				
From	Capelin	Cod	Mackerel	No class	Total
Capelin	21(91)	2(9)	0(0)	0(0)	23(38)
Cod	0(0)	25(96)	1(4)	0(0)	26(43)
Mackerel	1(9)	0(0)	10(91)	0(0)	11(19)
Total	22(37)	27(45)	11(18)	0(0)	60(100)

TABLE 5. Classification of 23 capelin and 44 cod schools measured in 1985 employing the quadratic classification functions generated from the 1986 data. Details of discriminant functions given in Table 3. Percentages in parentheses.

	Classified into species				
From	Capelin	Cod	Mackerel	No class	Total
Capelin	20(87)	3(13)	0(0)	0(0)	23(34)
Cod	2(5)	41(93)	1(2)	0(0)	44(66)
Total	22(33)	44(66)	1(1)	0(0)	67(100)

biased process. This is especially true for mackerel and capelin. In such cases, target strength appears to become an unpredictable quantity, dependent on unknown variations in packing density of the school, behavioral patterns, and the random occurrence of nonrepresentative single fish or echoes deemed to be single fish by the selection criteria. In addition, some misclassified single targets may contaminate the target strength data. This holds especially for cod, where the −50 dB mode would suggest, based on the fish length–target strength regression, the presence of 8-cm cod. We consider the presence of small cod with adult fish highly unlikely. This −50 dB mode is more likely either a function of an unknown behavioral variation or represents an unidentified organism. We conclude that species separations can be made employing mean target strengths, but only when target species have reasonably discrete target strength distributions (such as cod and capelin) and when the schooling structure of the targets allows the resolution of a reasonable number of single targets.

Classification by School Descriptors

Classification of cod, capelin, and mackerel schools by the school descriptors was highly successful. This success was achieved largely because of consistent and predictable differences in SPT among species. PP also had strong discriminatory power. All stepwise selections chose SPT first and PP second an discriminators of species. We believe that these measures integrate differences in acoustic reflection and resonance of schools which differ in size of individuals, internal school structure, and packing density. PP was positively correlated with target strength ($r = 0.50$, $P < 0.05$). SPT was negatively correlated with mean school density ($r = -0.29$, $P < 0.05$).

It is important to note that SPT and PP values must be interpreted in relation to the 0.8-ms pulse width (59 cm) used in this work. Density layers of acoustic targets separated by less than this distance could not be fully resolved. In addition, the curved base of the acoustic beam will further decrease the sampling resolution of horizontal layers of fish. This decrease in resolution will increase with depth as a result of the increasing width of the beam with range. For example, at 50 m, assuming that fish layers are normal to the acoustic axis, the effective vertical resolution increases to 79 cm. Thus, all but the larger cod may at times have schooled at densities too great for complete vertical resolution of single layers of fish. Despite this limitation, density layers separated by less than the pulse width may be partially resolved. The degree of partial resolution is thought to be the basis of the observed differences in SPT and PP.

We believe that the SPT and PP measures reflect internal school structure. Nearest neighbor distance (NND) has often been used as a criterion of internal school structure. Pitcher and Partridge (1979) showed that under laboratory conditions, NND averaged near 1 body length. A recent laboratory study of schooling structure under variable light conditions showed that mackerel maintain NND of 0.3–1.8 body length (Glass et al. 1986). In the present work, assuming icosahedral packing of fish with density layers normal to the acoustic axis, NND values were identical for mackerel and cod (3.2 mean body lengths, calculated from mean target strength of mackerel at sea applied to the regression of length on target strength). These NND values are higher than predicted by Pitcher and Partridge (1979), but considering the comparison involves field and laboratory data, the differences are not remarkable. Several other derivations of NND or volume occupied by each fish from field data showed values well above those predicted for cod, herring, and capelin (Radakov 1973; Serebrov 1976; Cushing 1977). The similarity of the theoretical values of NND and our empirically determined values supports the hypothesis that SPT and PP reflected actual nonrandom variations in school structure for cod and mackerel.

For capelin, PP probably did not represent actual vertical density spacing. Mean NND (10 body lengths) appeared to be inconsistent with that predicted by Pitcher and Partridge (1979). For capelin, resolution of peaks was probably aliased as the distance between density layers in relation to pulse width decreased. This interpretation is strengthened by the low value of SPT (1.5), which suggests that density layers were closely spaced. Use of a narrower pulse width would probably increase the discrimination power of PP.

The potential usefulness of the classification measures depends on their robustness against variations in acoustic system calibration and fish school parameters. We have attempted, by avoiding the use of unstandardized measures of voltage, to derive discriminating measures which are robust against variable system output. Potential variability in the fish school parameters, beyond that encountered here, and the effect of such variability on the success of the discriminant functions is more difficult to assess. The form, size, and density of fish schools are likely to vary seasonally and with changing environmental conditions (Radakov 1973). We caution that any attempt to use these discriminant functions outside the particular environment of this study will require a reassessment and recalibration of the quadratic coefficients. In particular for mackerel, which in inshore areas avoid boats and school at shallow depth, the values shown here may not be appropriate for deeper waters.

Classification in Other Systems

We have demonstrated a specific case of how signal feature extraction techniques can be applied to fisheries acoustics. The specific features found to be successful discriminators of species in the environment dealt with here, and the methods used to extract these features, should be regarded as being particular examples from a wide range of potential signal descriptors. In other systems, other methods and other features may provide good discrimination. For example, Fourier transformations can be employed to describe the wave forms of school and individual fish echoes (Holliday 1972; Deuser et al. 1979). We advocate that discriminant functions be developed on a case-by-case basis, employing an empirical approach, wherein the success of the classification is paramount. An ecological rationale will assist workers in identifying features likely to have discriminatory power.

Discriminant techniques are easily automated and well suited to taxonomic classification of acoustic signals (Fisher 1936). However, Fisher's technique was linear and required that the covariance matrices of the groups be homogeneous. We found that the covariance matrices of the school descriptors were heterogeneous, and we believe that this heterogeneity has a biological basis. For example, cod schools ensonified near the bottom were on average thicker than those found well off the bottom. Capelin and mackerel schools, by contrast, were thicker when located further off bottom. For all species, thicker schools were on average denser. Thus, cod schools near bottom were denser, but capelin and mackerel schools were denser when more pelagic. These differences are thought to reflect behavioral differences between cod, a species usually associated with the bottom, and capelin and mackerel, which are pelagic. Thus, heterogeneity of covariance matrices of these types of signal descriptors may be universal and require use of the quadratic approach.

In conclusion, we have shown that species classification of schooling fishes is possible using an array of discriminators extracted from the acoustic signal. These techniques are amenable to automated processing and in conjunction with integration and target strength assessment can provide data on fish abundance by species.

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