Effects of Sounds from a Geophysical Survey Device on Behavior of Captive Rockfish (*Sebastes* spp.)

Walter H. Pearson

Battelle, Marine Sciences Laboratory, 439 West Sequim Bay Road, Sequim, WA 98382, USA

John R. Skalski

Center for Quantitative Science, HR-20, University of Washington, 3737 15th Avenue N.E., Seattle, WA 98105, USA

and Charles I. Malme

BBN Laboratories, Inc., 70 Fawcett Street, Cambridge, MA 02238, USA

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Behavior of rockfish (*Sebastes* spp.) exposed to air-gun sounds was examined to establish parameters in a subsequent fishing experiment to determine the effects of a geophysical survey device on fishing success. Rockfish observed in a field enclosure showed startle and alarm responses during 10-min exposures to sounds from a single 1639-cm^3 air gun. For olive and black rockfish (*S. serranoides* and *S. melanops*), the threshold for the startle responses lay between 200 and 205 dB re 1 μPa. Under sound presentation, blue rockfish (*S. mystinus*) milled in increasingly tighter mills, and schools of black rockfish collapsed to the bottom. Vermilion (*S. miniatus*) and olive rockfish formed stationary schools near the bottom and, on sound presentation, either rose in the water column or moved to the bottom and became almost motionless. The general threshold for the alarm responses was about 180 dB re 1 μPa. Regression analyses of changes in depth distribution and shifts to active behaviors suggested that more subtle behavioral responses to sounds might become evident at 161 dB re 1 μPa. These initial responses were sustained only for a few minutes and may differ from those of unconfined fish.

Le comportement de sébastes (*Sebastes* spp.) exposés aux sons émis par un canon à air comprimé a été étudié afin d'établir les paramètres d'un essai de pêche visant à déterminer les effets des canons utilisés pour les levés géophysiques. Les sébastes observés dans une enceinte sur place ont présenté des réponses de surprise et d'alerte au cours d'expositions de 10 min aux sons émis par un canon à air comprimé de 1 639 cm^3. Dans le cas des sébastes olive et noir (*S. serranoides* et *S. melanops*), le seuil de ces réponses se situait entre 200 et 205 dB à 1 μPa. Sous l'effet des ondes sonores, les sébastes bleus (*S. mystinus*) se sont mis à tourner en rond en groupes de plus en plus serrés tandis que les bancs de sébastes noirs se sont dirigés vers le fond. Les sébastes vermillon (*S. miniatus*) et olive formaient des bancs stationnaires à proximité du fond et, sous l'effet des ondes sonores, ils se sont élevés dans la colonne d'eau ou se sont déplacés vers le fond et y sont demeurés pratiquement sans bouger. Le seuil de la réponse d'alerte était généralement de 180 dB à 1 μPa. Des analyses par régression des modifications de la distribution selon la profondeur et de l'apparition de comportements actifs portent à croire à l'existence de réponses comportementales aux sons moins apparentes à partir de 161 dB à 1 μPa. Ces premières réponses n'étaient maintenues que pendant quelques minutes et pourraient différer de celles des poissons non confinés.

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There has been concern that sounds generated by air guns and other acoustic devices used in offshore oil and gas exploration have been affecting the commercial hook-and-line fishery for rockfish (*Sebastes* spp.) along the California coast. Experimental studies have indicated that sounds from nonexplosive survey devices such as air guns are not lethal to fish, and physiological effects have been reported for fish only within a few metres of air guns (Falk and Lawrence 1973; R. W. Weaver and R. J. Weinhold, Alaska Department of Fish and Game, unpubl. data). For fish, sounds from nonexplosive survey devices are much more likely to result in behavioral changes than physiological damage. Fish detect and respond to sounds (for a review, see Tavolga et al. 1981; Schwarz 1985), and loud, abrupt sounds may produce startle and alarm responses in fish (Blaxter et al. 1981; Blaxter and Hoss 1981; Schwarz and Greer 1984). We are concerned here with the levels at which fish respond to sounds from geophysical survey devices and what their reponse is likely to be.

Air guns are the type of device most frequently used in geophysical surveys off California (Malme et al. 1986), and comparison of the known hearing abilities of fish with the characteristics of sounds from air guns indicates that marine fish can hear air-gun sounds. Malme et al. (1986) has found that single air guns and air-gun arrays produce sound in frequencies from 50 to 200 Hz and 20 to 150 Hz, respectively. Some air-gun arrays have frequency spectra extending to 500 Hz, and high-resolution seismic survey devices may have frequency spectra extending to 1000 Hz. Thus, the frequency spectra of the seismic survey devices cover the range of frequencies detected by most fish, for example, 50–3000 Hz for marine fish in general (Platt and Popper 1981; Hawkins 1981) and 10–250 Hz specifically for Atlantic cod (*Gadus morhua*) (Buerkle 1968; Chapman and Hawkins 1973; Offutt 1974).

Available information indicates that marine fish are quite likely to detect air-gun sounds for some distance from their source. Given the close match between spectra, the distance over which fish are likely to hear survey sounds can be estimated from consideration of (1) the fish's detection threshold, (2) the effects of sound pulse duration and background noise, (3) the source level of the device, and (4) the transmission loss (Pearson et al. 1987). On the basis of field experiments with Atlantic cod (Chapman and Hawkins 1973), marine fish can be expected to exhibit a detection threshold for continuous sound of about 80 dB re 1 μPa (hereafter, dB will be expressed as relative to a reference level of 1 μPa). Because sound pulses of short duration can heighten the detection threshold (Hawkins 1981), perhaps by as much as 50 dB for air-gun sounds (Pearson et al. 1987), the detection threshold for air-gun sounds can be expected to be 130 dB. Malme et al. (1986) gave values of 222 and 250 dB at 1 m as typical source levels for single air guns and arrays of air guns, respectively, and Greene (1985) reported a source level equivalent to 255 dB at 1 m for a 28-gun array used off California. Given a 250-dB source level for an array and a 25 log(R) transmission loss as indicated by the data of Malme et al. (1986) and Greene (1985), a detection threshold estimated at 130 dB implies that a fish can hear survey sounds at a distance of 63 km. If the transmission loss is 35 log(R), typical of shallow water, the distance at which fish may hear sounds from arrays is estimated as 2.7 km.

Although available information indicates that fish may hear survey sounds at some distance, the levels at which rockfish would respond to such sounds or the nature of any responses have not been determined. Sound levels well above the detection threshold are needed to elicit behavioral responses in herring (Blaxter et al. 1981; Blaxter and Hoss 1981). Also, air guns produce sounds that have the abrupt onset or instantaneous rise time important in eliciting startle and alarm responses in herring (Blaxter et al. 1981; Schwarz and Greer 1984). Because experimental observations of behavioral responses of rockfish to air-gun sounds have not been made, our aim was to determine the thresholds at which air-gun sounds elicit behavioral responses in rockfish and to describe the nature of any such responses. Also, the results of these behavioral observations were to establish experimental parameters for a fishing experiment (Pearson et al. 1987; Skalski et al. 1992) subsequently conducted to determine the effects of air-gun sounds on fishing success.

Between July 13 and July 18, 1986, we conducted a field experiment to determine the threshold at which sounds from an air gun produced a startle response or other behavioral changes in captive rockfish. A field approach was used because the sound characteristics could not be simulated even in a large laboratory aquarium (Parvulescu 1967; Chapman and Hawkins 1973; Hawkins 1981; van den Berg and Schuijf 1985). In five trials, we presented air-gun sounds to rockfish held in a field enclosure and simultaneously observed their behavioral responses.

Materials and Methods

Study Area

The study area in Estero Bay, north of Morro Bay, California, was selected because it offered sheltered water of acceptable visibility close to locations where rockfish could be readily captured (Fig. 1). During the experiment, seismic survey vessels were operating south of Pt. Sal, California, at least 65 km from our study area and, therefore, beyond the hearing of rockfish in our study area. After a survey to assess the visibility in the general area and ensure that the site was without potential sound shadows, the field enclosure was deployed off Cayucos, California, at approximately 35°25.8′N and 120°53.8′W. The enclosure location had a water depth of 14 m with a soft bottom of fine sand and silt. From the enclosure location, the bottom sloped southwards at approximately 10 m in 1 km.

Sound Production

A 35-m utility vessel, M/V *NAUTILUS*, supported the sound production systems. A single 1639-cm^3 (100-in.^{3}) air gun operated at 4500 psi (1 psi = 6.895 kPa) was chosen in order to provide a simple, well-defined sound source for the field trials. Also, an air gun was selected because this type of device is the most frequently used in geophysical surveys off California (Malme et al. 1986). The source level for this air gun was approximately 223 dB. A diesel-driven air compressor provided high-pressure air in sufficient volume to operate the gun at a firing rate of six pulses per minute, the rate used in all tests. The compressor was mounted on vibration isolation supports to reduce sound radiation into the water. The air gun was attached to an umbilical cable containing the air hoses and control wires and to a towing cable with a surface float. The float supported the gun at a depth of 6 m, a depth typical of industry practice. For close-range tests where precise control over the distance to source was needed, an inflatable boat was used to manually control the air-gun position.

Sound Monitoring

The sound monitoring, acoustic data acquisition, and data analysis systems were also installed on the M/V *NAUTILUS*. The source level and sound output of the air gun were monitored during all of the tests by a hydrophone 12 m away. A second hydrophone was installed on a spar buoy and deployed near or in the fish enclosure during the behavioral observations. This buoy was equipped with a radio transmitter to relay the acoustic signals back to the measurement and recording systems on the M/V *NAUTILUS*. For the first trial, in which the sound boat began discharging the air gun at 6 km from the enclosure, the buoy was anchored 21 m due north of the enclosure with the hydrophone at a depth of 3.7 m, which was equal to the depth of the floor of the enclosure. For the second and third trials, the buoy was deployed at the eastern side of the enclosure with the hydrophone at a depth of 2.4 m. The depth of the hydrophone was changed to position it at the midpoint of the depth distribution of the fish observed in the enclosure. For the remaining trials, the hydrophone was deployed in the center of the enclosure at a depth of 2.4 m.

The signals from the hydrophones were amplified and recorded using a multichannel analog tape recorder, a storage oscilloscope, and a strip chart recorder. A real-time narrowband spectrum analyzer was used to analyze selected data samples during an experiment to obtain near-real-time hard copy records of pressure waveforms and pressure level spectra. All equipment was calibrated to obtain the system pressure sensitivity with a reference of 1 V/μPa.

To estimate the potential effect of temperature and salinity gradients on sound velocity, we used a temperature and conductivity bridge to obtain depth profiles of sound speed to near

FIG. 1. Location of the fish enclosure near Cayucos Point used in the behavioral experiment.

bottom or 20 m. To measure the variation in the sound levels with depth, sound measurements were made within the enclosure with the air gun at a range of 50 m and with the hydrophone positioned at various depths within the center of the enclosure.

The signals received by the spar buoy hydrophone were recorded for all sound presentations and were analyzed on a pulse-by-pulse basis to determine sound exposure levels at the enclosure. We found that sampling of every third pulse was adequate to define the variability in exposure levels. The maximum positive and negative pressure values for each sampled signature were entered into a data file for each presentation. For the trials within metres of the enclosure, the acoustic travel time for the pulse was also measured to determine range. The effective peak pulse level in decibels re 1 μPa is defined as follows:

$$(1)\quad P_m = \frac{20 \log (P_+ - P_-)}{2} P_{\text{ref}}$$

where P_+ is the maximum positive pressure in micropascals, P_- is the maximum negative pressure (micropascals), and P_{ref} is the reference presure, 1 μPa. The mean peak pressure level and standard deviation were determined for each sound presentation.

Experimental Enclosure

The field enclosure used for behavioral observation consisted of an octagonal PVC pipe frame and float system supporting a net of 6 mm off-white knotless nylon mesh. The net was shaped as an octagonal prism with a flat top and flat bottom. The net measured 4.6 m across the diagonals and was 3.6 m deep. The enclosure was anchored at four points so that the net top was just below the water surface. A door in the center of the net top allowed observation of the captive fish with a viewing box from a rubber raft moored over the net top. For each trial, we adjusted the depth of the net floor so that all fish in the net were visible from the water surface through the viewing box.

Procedures for Trials

There were five behavioral trials with two to six sound presentations per trial. In Trials 1 and 2, the sound level during each succeeding 10-min presentation was increased by having the sound boat come to half the distance of the previous presentation. In subsequent trials, staircase regimes of sound levels were presented by directing the sound boat to decrease or increase the range depending on whether the fish showed any behavioral response. The staircase regime of sound levels was intended to estimate the threshold at which behavioral response occurred and is a standard approach to stimulus presentation for threshold determination (Cornsweet 1962). Behavior of the fish was observed before, during, and after sound exposure.

The afternoon before each day's trials, rockfish were captured near rock pinnacles in Estero Bay, California, by trolling with lures and barbless hooks in depths from 10 to 30 m. On

TABLE 1. Rockfish used in the behavioral experiment at Estero Bay, July 13–18, 1986.

Observed trial	Date of capture	Fish	Fish in enclosure
1	July 13	Blue rockfish, *S. mystinus*	13
		Olive rockfish, *S. serranoides*	7
2	July 14	Olive rockfish, *S. serranoides*	1
		Vermilion rockfish, *S. miniatus*	2
3	July 15	Olive rockfish, *S. serranoides*	6
		Vermilion rockfish, *S. miniatus*	7
4	July 15	Same fish as Trial 3	
5	July 16	Black rockfish, *S. melanops*	17
		Brown rockfish, *S. auriculatus*	1

capture, excess gas in the gas bladders of each fish was released by puncture with a hollow needle. Without release of excess gas, rockfish can be expected to suffer high mortality (Hart 1973). The fish were then placed into a holding tank with continuously flowing seawater on the F/V *BONNIE MARIETTA*. Within 3 h of capture, the rockfish were transferred into the field enclosure. Fish from the day's trials were released before introduction of new fish for the next day's trials. Fish were acclimated at least overnight before testing.

Each day's batch of fish varied in number and species composition because of variation in the daily catch (Table 1). An effort was made to test a variety of rockfish. For the first two trials, the selection strategy was to choose the most abundant fish in the catch to place 20 or all available fish into the enclosure. During the acclimation period for Trial 2, the large vermilion rockfish (*S. miniatus*) killed the smaller rockfish. Consequently, vermilion rockfish were not mixed with smaller rockfish thereafter. In Trial 5, three of 17 black rockfish (*S. melanops*) died during acclimation.

To determine thresholds for behavioral responses, five experimental trials (one per day) were conducted. Each trial began with a control observational period during which the fish were observed continuously through a viewing box for at least 30 min. All observations were made by one observer. Notes on the behavior of the fish were recorded by a second investigator on waterproof paper at 2-min intervals. Presentations of air-gun sounds were 10 min each and followed the control period. Behavioral observations were continuous, and notes on behavior were recorded at 1-min intervals. Two to six sound presentations were made per trial, depending on weather and the distance that the sound boat had to move between presentations. Between sound presentations, observations were made continuously for a minimum of 16 min with notes recorded at 2-min intervals. If more than 40 min separated the successive sound presentations because of the time needed to reposition the sound boat, observations for 10 min with notes recorded at 1- or 2-min intervals were made just after and just before the sound presentations. Observations were also made at 2-min intervals between these pre- and posttreatment observational periods. The sound levels measured during the presentations are given in the Results.

From the available information, we developed criteria for scoring each sound presentation. Before the experiment, three types of behavioral responses to loud, abrupt sounds were anticipated from observations of captive herring: avoidance, alarm, and startle (Blaxter et al. 1981; Schwarz and Greer 1984). Avoidance responses could not be observed in the field enclosure, although startle responses were. We also observed a combination of general increases in activity and changes in schooling and water position, all of which we have categorized as ''alarm'' on the basis of analogy with the descriptions of Blaxter et al. (1981). For each sound presentation, the intensity of alarm and startle responses was scored according to the following criteria modified from Blaxter et al. (1981): 0, no response; 1/2, one or two fish respond; 1, several fish respond; 2, up to half the fish respond, 3, more than half the fish respond. Although these scores provided general indications of the behavioral responses, these data could not support the comparison of behavior during sound presentation with that before and after presentation.

Besides scoring intensity of alarm and startle responses, we used the 1- and 2-min observations to tabulate the number of fish observed in various categories of behavior as well as position in the water column. The behavioral categories were (1) holding position (undirected), (2) holding position (directed), (3) directed moving, (4) eddying, (5) milling, and (6) other moving. Similarly, the categories of water column position were (1) at the bottom, (2) in the lower one third, (3) in the middle one third, and (4) in the upper one third. In these tabulations, fish were recorded in both a behavioral category and a water column position. Descriptions of the behavioral categories appear in the Results.

Statistical Analyses

Graphical displays and multiple regression analyses were used to examine the relationship between sound exposure levels and changes in the vertical distribution and behavior of the fish in the field enclosures. These analyses were restricted to Trials 1, 3, 4, and 5 because Trial 2 (with three captive fish) had too few fish for appropriate tests of effects based on the percent change in activity patterns.

For the vertical distribution of the rockfish in the enclosure, a linear contrast of the form

$$(2)\quad L_i = \text{(percent of visible fish in upper two thirds of enclosure)} - \text{(percent of visible fish in lower one third of enclosure)}$$

constructed for each individual observational period was plotted as a function of time and exposure. For response variable (2), the higher the value, the more fish were in the upper two thirds of the water column.

To reduce the dimensionality of the data in summary graphs, the behavior exhibited during a trial was translated to a linear contrast. For Trial 1 data, the 2-min observations were translated to the following linear contrast:

(3) L_i = [3 (number of fish milling)
+ 1 (number of fish with directed swimming)
− 1 (number of fish eddying)
− 3 (number of fish holding)]
÷ (number of fish visible).

The values of L_i in Equation 3 were then plotted as a function of time and treatment exposure. For Trials 3, 4, and 5, the individual observations on fish behavior were translated to the following linear contrast:

(4) L_i = [3 (number of fish engaged in other moving)
+ 1 (number of fish milling)
− 1 (number of fish eddying)
− 3 (number of fish holding)]
÷ (number of fish visible).

Other moving was not observed in Trial 1 but was in Trials 3 through 5. The particular forms of response variables (3) and (4) were selected because they represent orthogonal contrasts for linear trends among behavioral categories. Additional comparisons based on the quadratic and cubic responses were not analyzed. For both response variables (3) and (4), the higher the value, the more active were the fish.

The regression analyses used indicator (dummy) variables to adjust for trial effects related to species composition, weather, or other between-trial differences. After adjustment for trial effects, the independent variables associated with sound levels of an exposure (mean peak pressure in decibels re 1 μPa and the square of mean peak pressure in decibels re 1 μPa) were entered into the regression model to determine their association with the response variable. To assess effects of exposure levels on the vertical distribution of the fish in the enclosure, the dependent variable selected for analysis was

(5) Y_i = absolute value of the difference between the percent of visible fish in the upper two thirds of the enclosure during the exposure and preexposure periods of sound presentation ($i = 1, \ldots, 16$).

The position of the rockfish school in the water column varied with species, and changes in response variable (5) indicate sound-induced movement of the fish school either up or down in the water column. Analysis of variable (5) was based on data collected during the entire sound exposure period.

To assess effects on behavioral patterns, the percent of fish eddying and the percent of fish engaged in milling or other moving were evaluated. In both cases, the dependent variable used in the analysis was

(6) Y_i = absolute value of the difference in the percent of visible fish engaged in a behavior pattern between the exposure period and preexposure periods of a sound presentation ($i = 1, \ldots, 16$).

Changes in variable (6) indicate shifts from one behavioral category to another. Response variable (6) was analyzed using just the observations from the first 5 min of sound exposure.

Results

Sound Characterization during Trials

The weather conditions during the behavioral experiment were usually calm with a few brief periods of moderate winds. As a result, a warm surface layer was observed in the temperature profile data during most of the experimental period (Trials 1, 3, 4, and 5). This produced downward refracting conditions as shown by sound velocity profiles, although earlier wind-driven mixing had produced a more uniform sound velocity profile for Trial 2. Detailed tabulations of the depth profiles of temperature, salinity, and sound velocity appear in Pearson et al. (1987).

The ambient acoustic noise in the Estero Bay study area (65 and 75 dB) was typical of shallow-water areas in that it was influenced primarily by wind noise (up to 94 dB at 400 Hz) and biological noise (pistol shrimp, 97 dB at 6.3 kHz) with some low-frequency contributions from sporadic small craft traffic (80 dB at 16 Hz). Radiated noise from the M/V *NAUTILUS* moving at about 5.5 kn (10.2 km/h) had dominant lines in the spectrum (127 dB from 200 to 800 Hz) from slightly cavitating propellers. Even during a fullpower backdown, noise from the M/V *NAUTILUS* (136 dB at 120 Hz) was more than 50 dB less (a factor of 0.003) than the peak pressure level at the same distance (110 m) from the air gun. Radiated noise from the F/V *BONNIE MARIETTA* moving at slow speed (estimated 3 kn or 5 km/h) showed a tonal of 103 dB at 40 Hz produced by the propeller or about 20–30 dB above the local ambient noise level.

The mean peak pressures measured at the field enclosure during each sound presentation appear in Table 2. Additional measurements were made in the enclosure for an average source distance of 50 m in order to determine the variation of peak pressure level with depth (Table 2). Generally, the pressure level decreased 4 dB for a 1.5-m decrease in depth. Examples of the observed pressure–time waveforms (i.e. air-gun signature) and their associated pressure level spectra (Fig. 2 and 3) illustrate the change from an abrupt signature to a ramped signature as the distance between the air gun and the enclosure increased. These signature changes were due to the shifts in the relative influence of bottom and surface reflections.

Description of the Behavioral Changes

The captive rockfish exhibited a number of well-defined behaviors so that we were able to tabulate the number of fish observed in different behavioral categories at each observation during control periods and sound presentations. Detailed data tabulations appear in Pearson et al. (1987).

Under control conditions, the rockfish exhibited the behavior described by Keenleyside (1979) for what he termed a relatively stationary school. The fish generally hovered or held position in the water column (holding position, Fig. 4). When a current was present, the fish oriented parallel to each other and faced into the current (holding position, directed, Fig. 4). When the current slackened or was changing direction, individuals faced in different directions (holding position, undirected, Fig. 4).

Several types of movement were observed under control conditions. Undirected movement or eddying (Fig. 4) occurred intermittently. Fish would cease holding position to move slowly around the enclosure in meandering rather than directed or circular paths. Eddying was similar to the "short radius behavior" described by Keenleyside (1979) but with continuous, smooth movement rather than jerky motions. The blue rockfish (*S. mystinus*) exhibited directed movement (Fig. 4) in which the fish oriented parallel to one another and facing into the current. The polarization of the school was maintained as individual fish inched forward into the current until they reached the enclosure wall where they would turn, swim slowly to the back of the school, reorient into the current, and begin to inch forward again. Milling (Fig. 4) has been described by Keenleyside (1979) and is a special form of schooling behavior

TABLE 2. Chronological list of test ranges and peak pressure in the behavioral experiment in Estero Bay. Sound levels are dB re 1 μPa. P_+, maximum positive pressure; P_-, maximum negative pressure; P_m, effective peak pressure as defined in Equation 3 in Materials and Methods; SD, standard deviation of P_m.

Date and time	Range (m)	P_+ (dB)	P_- (dB)	P_m (dB)	SD (dB)
Trial 1					
July 14					
1136	5800	137.6	137.1	137.4	1.2
1214	2900	154.7	151.2	153.2	1.0
1303	1500	158.4	159.0	158.7	2.5
1332	760	160.9	161.4	161.2	3.1
1352	350	175.3	177.9	176.7	2.6
1429	185	178.2	178.2	178.2	1.7
Trial 2					
July 15					
0843	1760	156.2	154.7	155.5	1.3
0953	150	181.1	184.7	183.1	1.0
1053	100	187.2	184.8	186.1	0.9
1254	46	194.7	195.0	194.9	1.6
1354	59	194.8	192.0	193.5	1.0
Trial 3					
July 16					
0950	11	206.3	207.3	206.8	1.6
1126	225	175.6	176.5	176.0	1.4
Trial 4					
July 17					
0814	30	197.0	201.3	199.4	0.9
0914	51	193.0	189.6	191.5	0.8
Depth profiles					
July 17					
0940	62	190.0	187.5	188.8	3.1
0944	50	195.2	190.7	193.7	0.9
0946	47	192.1	189.2	190.7	1.0
0950	49	190.6	185.2	188.3	0.6
Trial 5					
July 18					
0816	17	203.2	206.6	205.1	2.2
0916	135	182.4	177.7	180.4	0.6
1016	65	190.3	189.0	189.7	0.8
1123	106	183.6	181.6	182.7	0.4
1230	66	189.6	186.8	188.3	1.2

in which the fish follow each other in a closed circle. Under control conditions, eddying blue rockfish would occasionally coalesce into a short-lived mill, but intense milling was observed only under sound presentation. Other moving behaviors observed under control conditions included swimming up and down through the water column and back and forth along the enclosure wall.

Behavioral Responses to Sounds from the Air Gun

The effects of sound exposure on the behavior of captive rockfish were evident as (1) shifts in the vertical distribution (either up or down), (2) shifts in behavior, and (3) the occurrence of alarm and startle responses.

Figures 5 to 8 depict the linear contrasts used to indicate changes in water column position (response variable (2)). In Fig. 5 to 8, each vertical line represents the result of the linear contrast for one observation. The longer the line below the zero point, the more fish were observed in the lower one third of the water column. The longer the line above the zero point, the more fish were observed in the upper two thirds of the water column. Figures 9 to 12 depict the linear contrasts used to indicate shifts from holding through eddying to milling (response variable (3) for Trial 1 and response variable (4) for Trials 3, 4, and 5). In Fig. 9 to 12, the higher the line above the zero point, the more fish were observed in milling or other moving. The lower the line below zero, the more fish were observed in holding.

Plots of the percentage of rockfish in either the upper two thirds or lower one third of the field enclosure (Fig. 5 to 8) indicate shifts in vertical distribution under exposure to high sound levels relative to the preexposure observations (response variable (2)). The 176.7- and 178.2-dB exposures of Trial 1, the 206.8-dB exposure of Trial 3, the 199.4-dB exposure of Trial 4, and the 205.1-, 189.7-, and 188.3-dB exposures of Trial 5 all show substantial shifts in water column position associated with the treatment.

Similarly, plots of the time sequence of the behavioral contrasts (3) and (4) indicate definite changes in behavioral patterns under high sound exposures (Fig. 9 to 12). The 206.8-dB exposure of Trial 3, the 199.4-dB exposure of Trial 4, and the

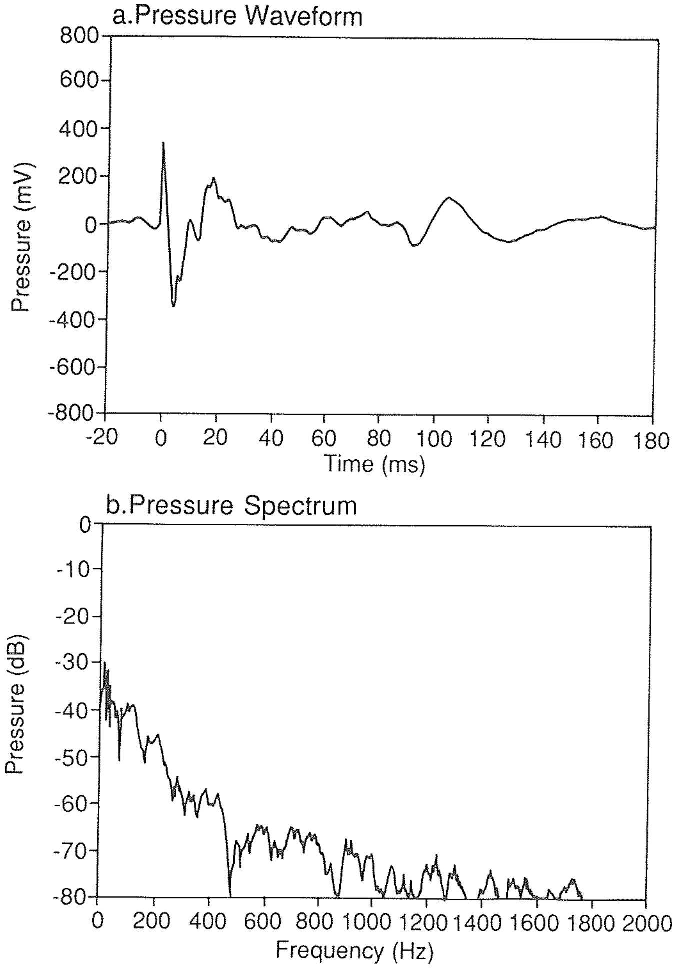

FIG. 2. Air-gun (a) pressure–time signature and (b) pressure level spectrum measured at a depth of 6 m in the enclosure for a source distance of 21 m.

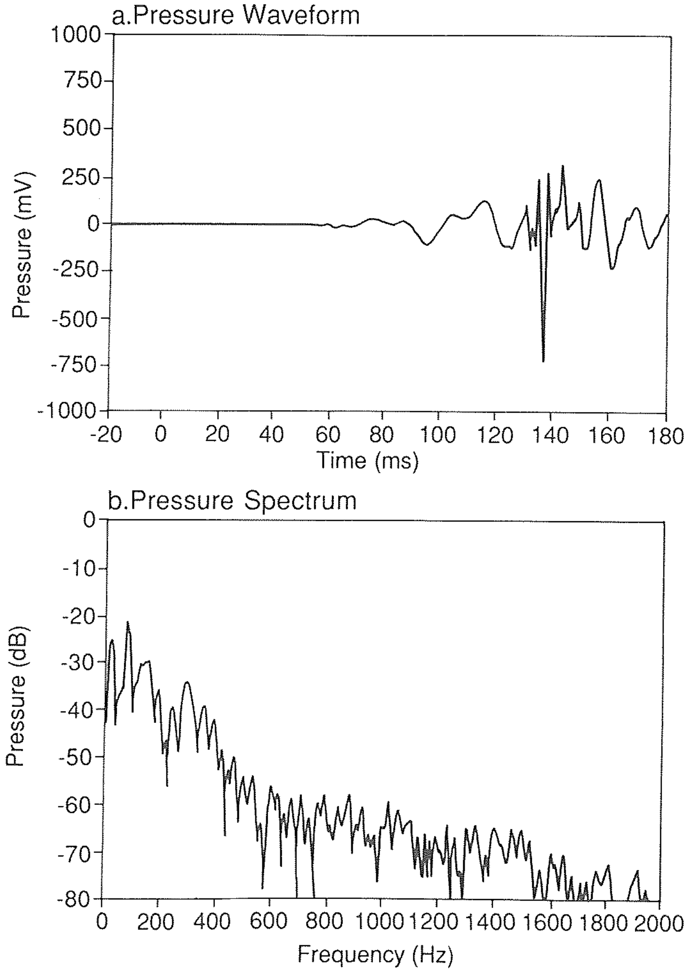

FIG. 3. Air-gun (a) presure-time signature and (b) pressure level spectrum measured at a depth of 2.5 m in the fish enclosure for a source distance of 214 m.

205.1-dB exposure of Trial 5 show clear signs of a shift in behavior between preexposure and exposure periods. Taken together, the data in Fig. 5 to 8 suggest a general threshold of about 180 dB for alarm responses elicited by air-gun sounds.

For response variable (2) concerning shifts in vertical distribution of fish within the enclosure, regression analysis revealed a significant relationship with the maximum peak pressure level (P_m in decibels; Table 2) during exposure ($P(t_{11} > 3.6336) = 0.002$). The percent change between control and emission periods increased significantly (Fig. 13) as the sound level increased. Utilizing the least-square fit of the response model (taking into account a weighted mean for the intercept with respect to fish group effects), an estimate of the minimum sound level to elicit a treatment effect can be estimated by setting the dependent variable equal to zero and solving for the sound level. Thus, setting $y_i = -1.64355 + 0.01015\text{dB} = 0$ yields $\text{dB} = 161.9$. Therefore, the experimental results suggest that rockfish may show changes in their vertical distribution within the enclosure at sound levels above 162 dB ($\text{CI}(151.7 < \text{dB} < 172.1) = 0.90$).

Similar regression analysis of the percent change in milling and other moving between preexposure and exposure periods (response variable (3)) indicates a significant relationship with the level of sound exposure ($P(t_{11} - 2.3843) = 0.018$). This relationship was not significant ($P(t_{11} - 0.5946) = 0.285$) when data from the entire exposure period were analyzed. Similarly, a significant relationship betwen the absolute change in percent eddying behavior and sound level was observed during the trials ($P(t_{11} - 2.061) = 0.032$), but no significant relationship was observed between shifts in eddying behavior and sound levels based on analysis of data for the entire exposure periods ($P(t_{11} - 0.7050) = 0.248$). Thus, rockfish increase their activity when exposed to air-gun sounds but return to preexposure behaviors within the exposure periods.

The dose–response relationships observed during the trials indicate the sound levels above which shifts in behavior patterns may become evident. From the regression relationship for milling behavior, milling would occur above an estimated sound exposure level of 167.6 dB ($\text{CI}(139.5 < \text{dB} < 194.8) = 0.90$). Similarly, eddying behavior began to occur above a sound exposure level of 153.6 dB ($\text{CI}(128.9 < \text{dB} < 178.3) = 0.90$). Therefore, the behavioral observations indicate that, in general, behavioral responses to air-gun sounds may be observed starting as low as 161 dB (i.e. average of 161.9 for changes in depth, 167.6 for changes in milling, and 153.6 for changes in eddying).

Alarm and Startle Responses

When exposed to air-gun sounds, black and blue rockfish responded as a school whereas vermilion and olive rockfish (*S. serranoides*) responded more individually. Under control conditions, blue and black rockfish typically formed schools

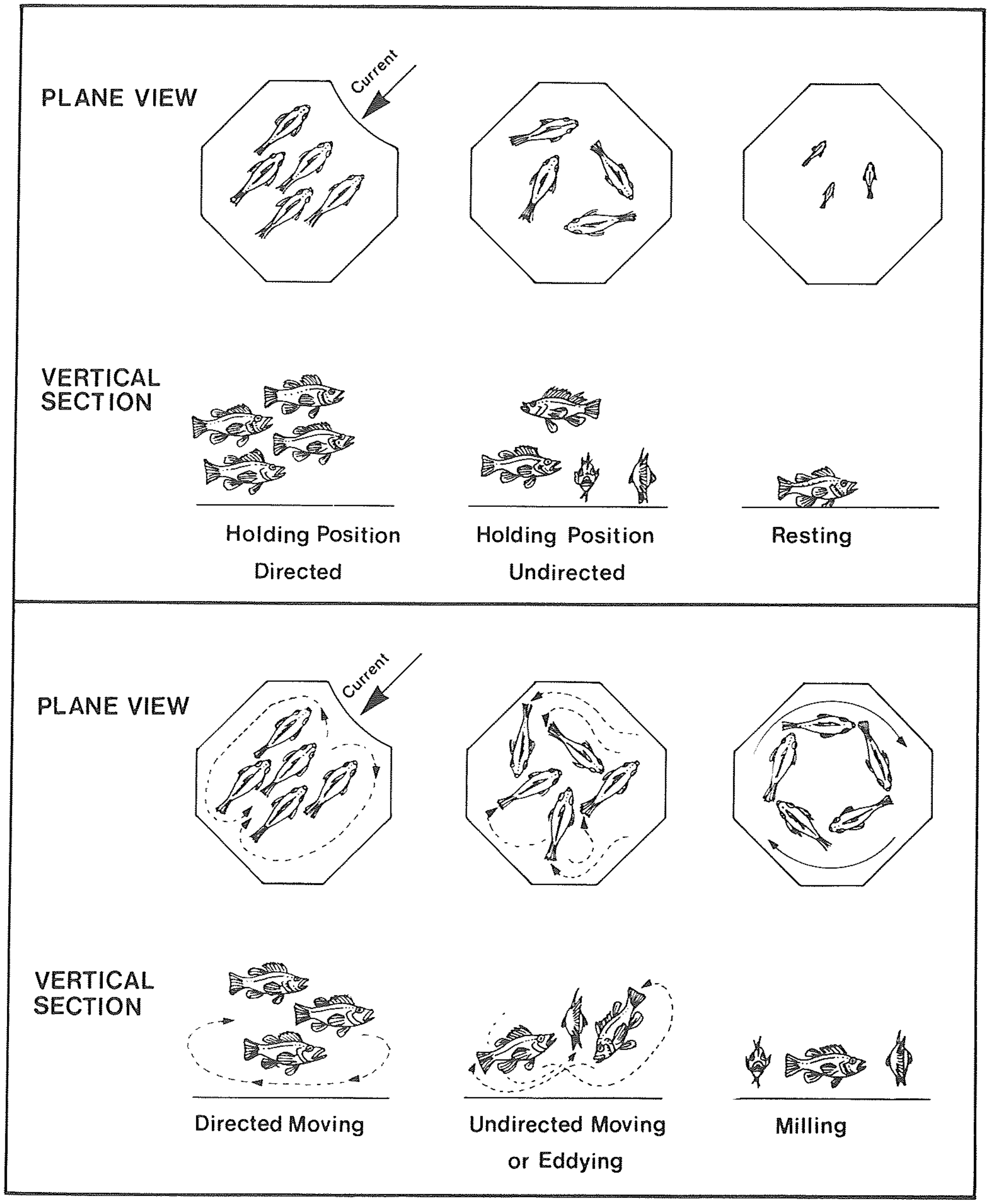

FIG. 4. Behaviors of captive rockfish in the enclosure of the behavioral experiment, May 1986.

off the bottom. Under sound exposure, blue rockfish formed a tight, rapidly circling mill, and the stationary schools of black rockfish collapsed to the bottom where they remained unpolarized and unsynchronized. Under control conditions, the vermilion and olive rockfish typically hovered at the bottom. Under sound exposure, individuals either rose in the water column and eddied at increased speed or moved closer to the bottom and became almost motionless.

Startle responses were either flexions of the body followed by rapid swimming (olive rockfish) or a series of shudders or tremors with each air-gun discharge (black rockfish). The startle responses in the olive rockfish were given to individual air-gun discharges during the first minute and resembled a Mauthner-type startle response (Blaxter et al. 1981; Schwarz and Greer 1984; Eaton and Nissanov 1985). Startle responses were observed at and above 205 dB (Table 3). Except for one startle response in one black rockfish at 190 dB, none were observed at and below 199 dB. The threshold for the startle responses in olive and black rockfish appears to be between 200 and 205 dB. No startle responses were observed in vermilion or brown rockfish up to the maximum exposure of 207 dB. Blue rockfish showed no startle responses below 180 dB but were not tested above 180 dB.

Alarm responses were observed at and below the sound exposure levels where startle responses were evident (Table 3). Alarm responses in the blue and black rockfish were first observed at lower levels than those in the vermilion and olive rockfish. Alarm responses in blue and black rockfish were first observed at 177 and 180 dB, respectively. In two trials with vermilion rockfish, alarm responses were first observed at 186 and 195 dB. For olive rockfish, alarm responses were observed above 199 dB but not at 192 dB. Strong alarm responses were noted from 178 to 207 dB, the highest level tested. Alarm responses increased in occurrence and intensity as the sound intensity increases (Table 3). Although the character of the alarm response varied with the species of rockfish examined, the data in Table 3 suggest that a general threshold for behavioral responses to sounds of a single air gun was about 180 dB.

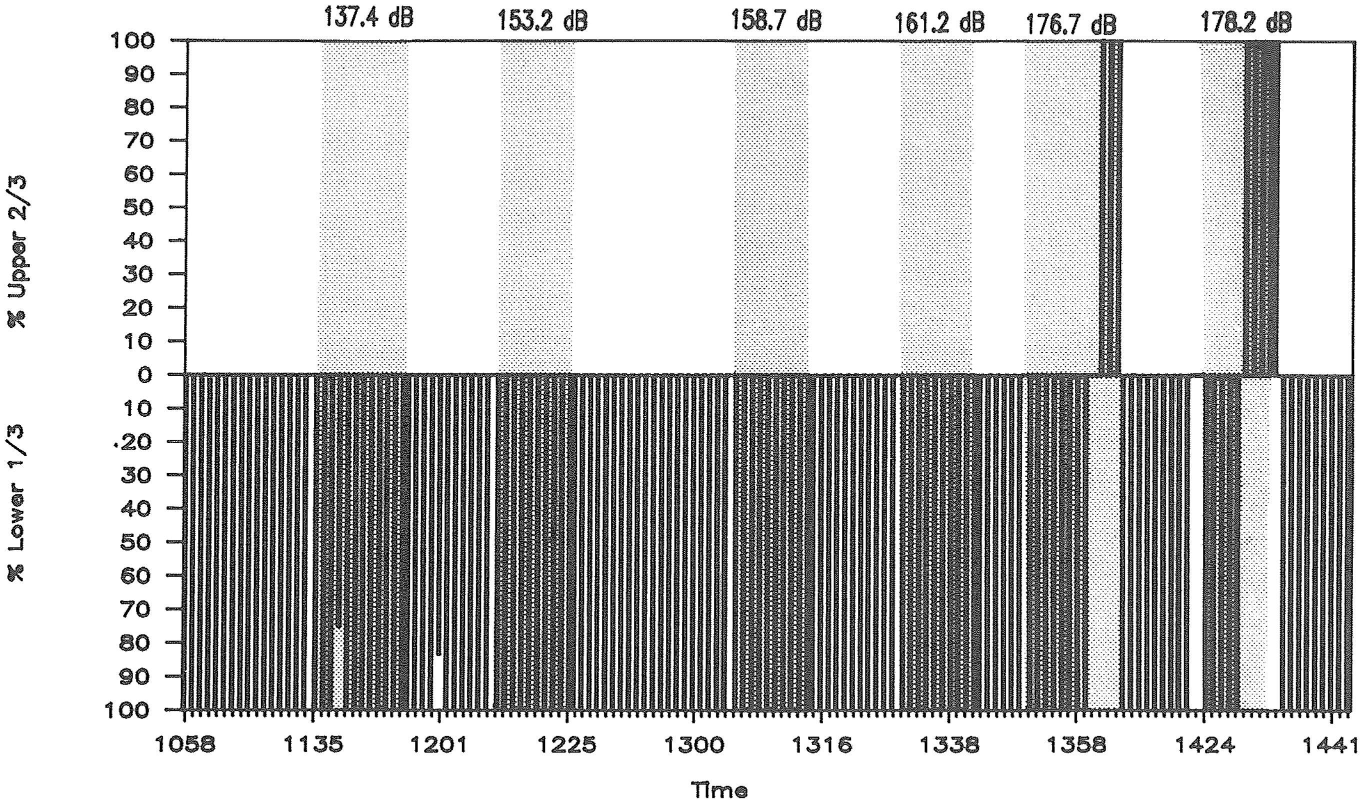

FIG. 5. Relative vertical position of rockfish in the water column of the enclosure per observation period during emission (shaded background) and nonemission (clear background) periods for Trial 1.

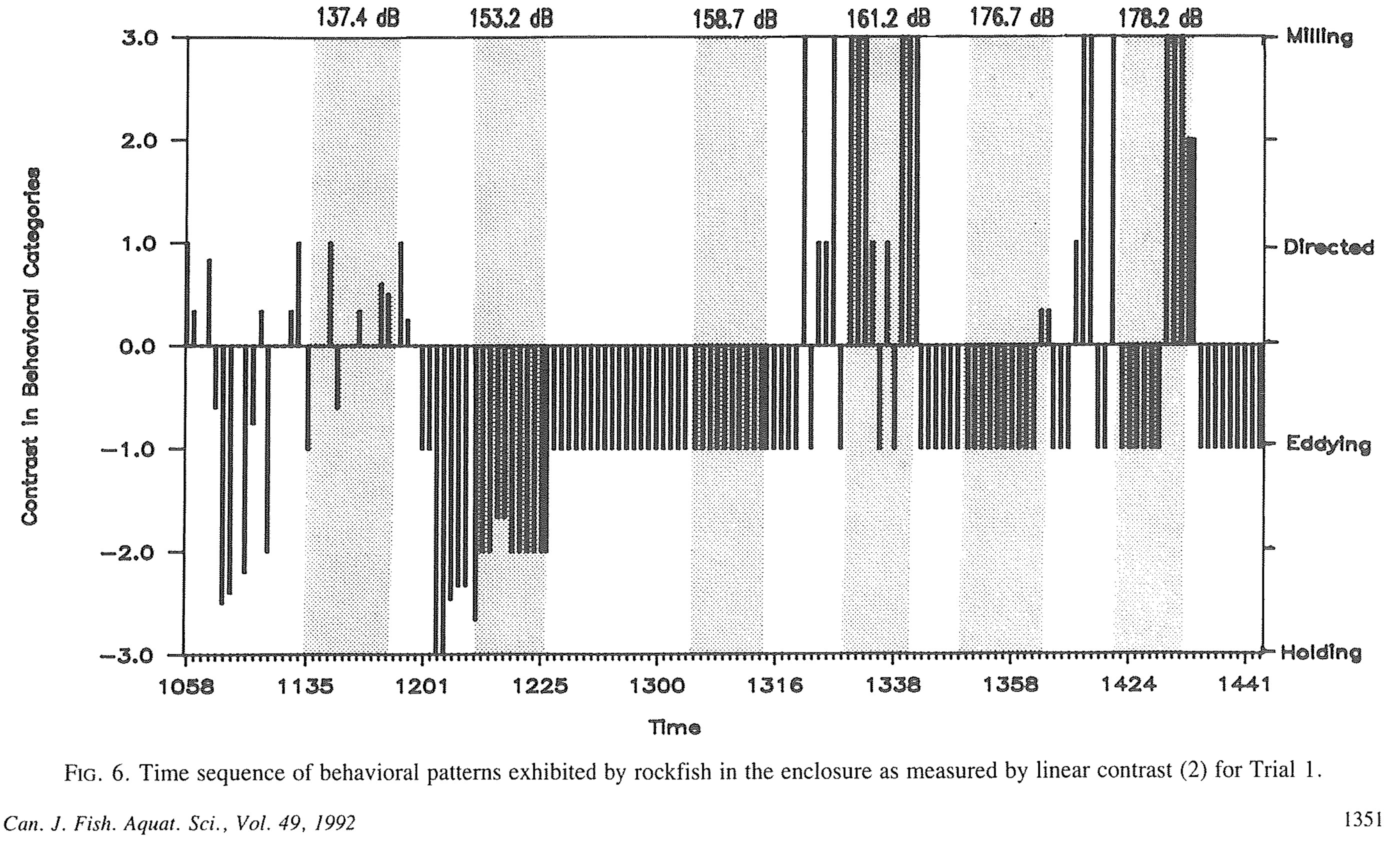

FIG. 6. Time sequence of behavioral patterns exhibited by rockfish in the enclosure as measured by linear contrast (2) for Trial 1.

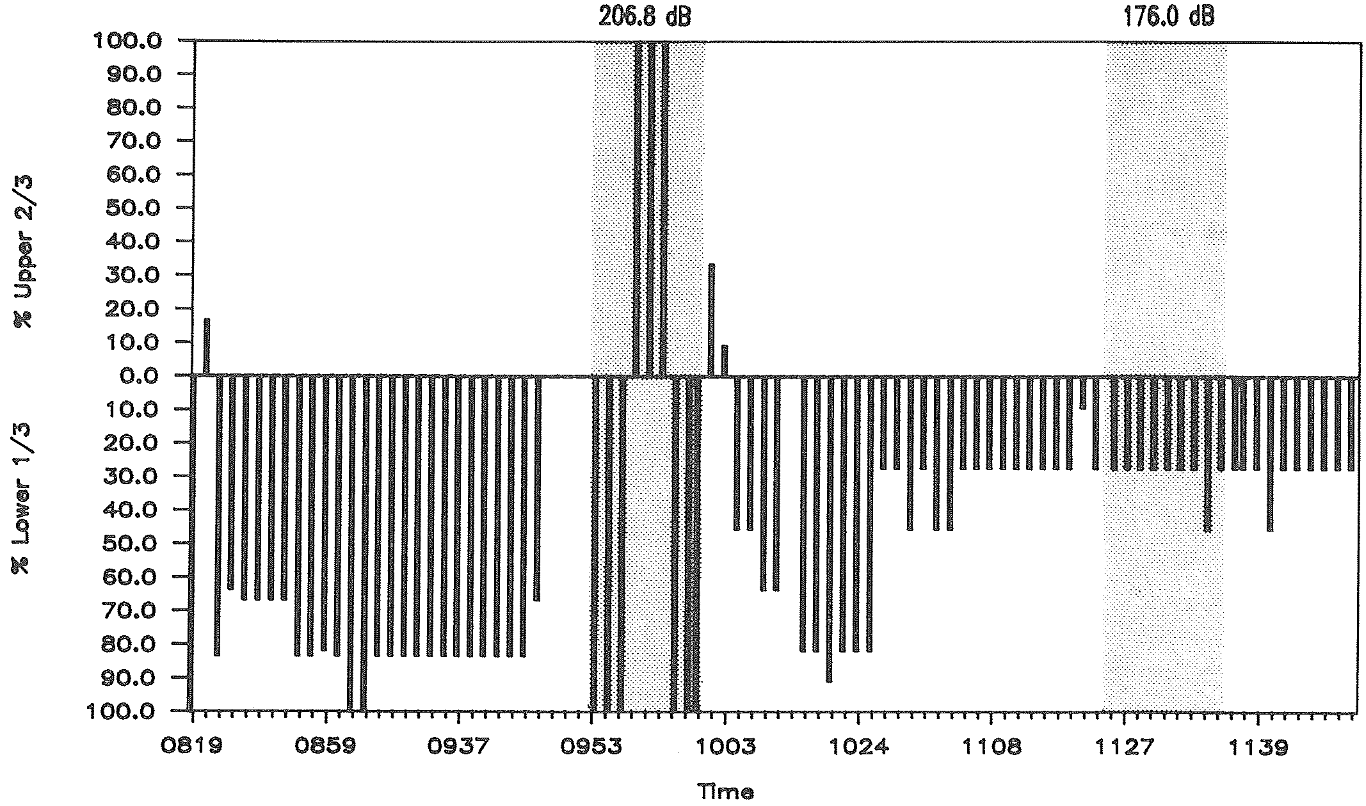

FIG. 7. Relative vertical position of rockfish in the water column of the enclosure per observation period during emission (shaded background) and nonemission (clear background) periods for Trial 3.

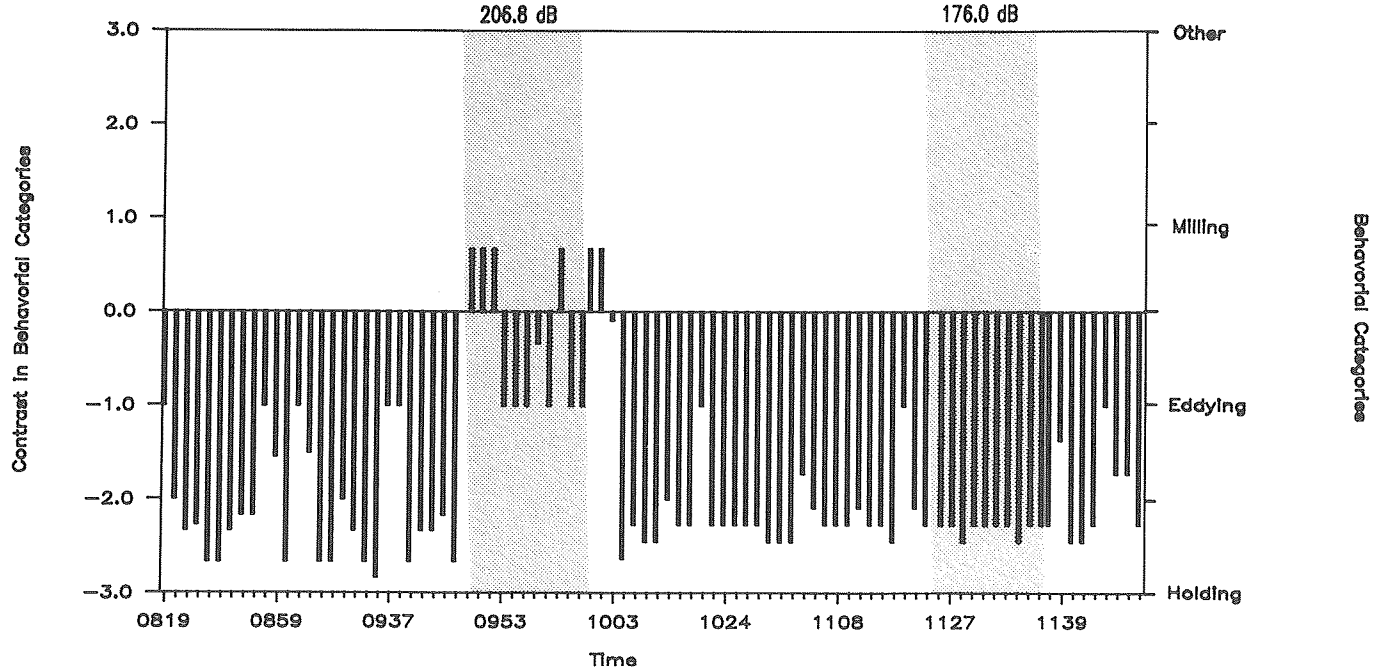

FIG. 8. Time sequence of behavioral patterns exhibited by rockfish in the enclosure as measured by linear contrast (3) for Trial 3.

Discussion

The behavioral experiment clearly showed that several rockfish species react to air-gun sounds with alarm and startle responses, but that the character and extent of such responses differ with species and sound level. Avoidance and other more subtle behavioral responses may occur, but the limitations of the experimental enclosure would have prevented their expression. Our behavioral observations alone cannot confirm or deny the existence of avoidance.

The alarm responses observed here appear to be extensions of behaviors typically seen or expected in escape from predators. Tight mills and "flash expansions" or loss of polarization have been observed for schools under attack by predators

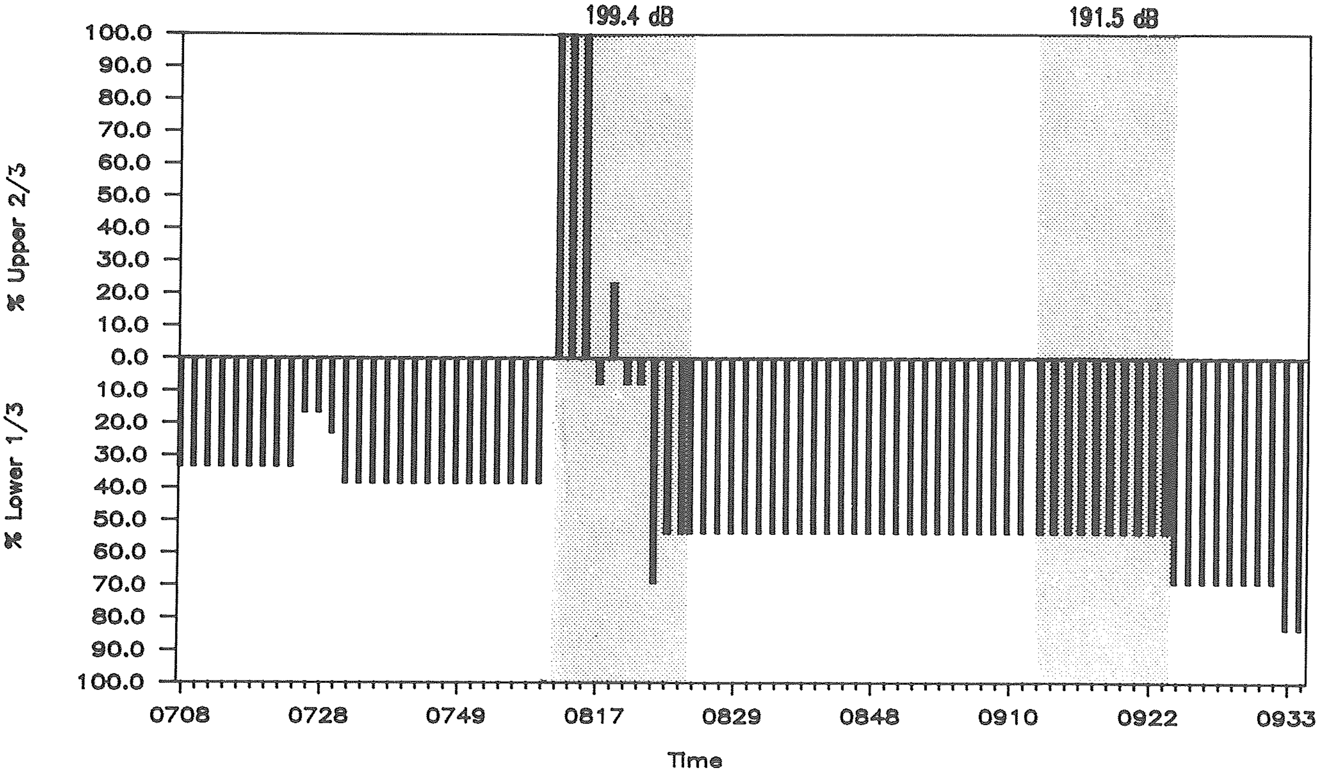

FIG. 9. Relative vertical position of rockfish in the water column of the enclosure per observation period during emission (shaded background) and nonemission (clear background) periods for Trial 4.

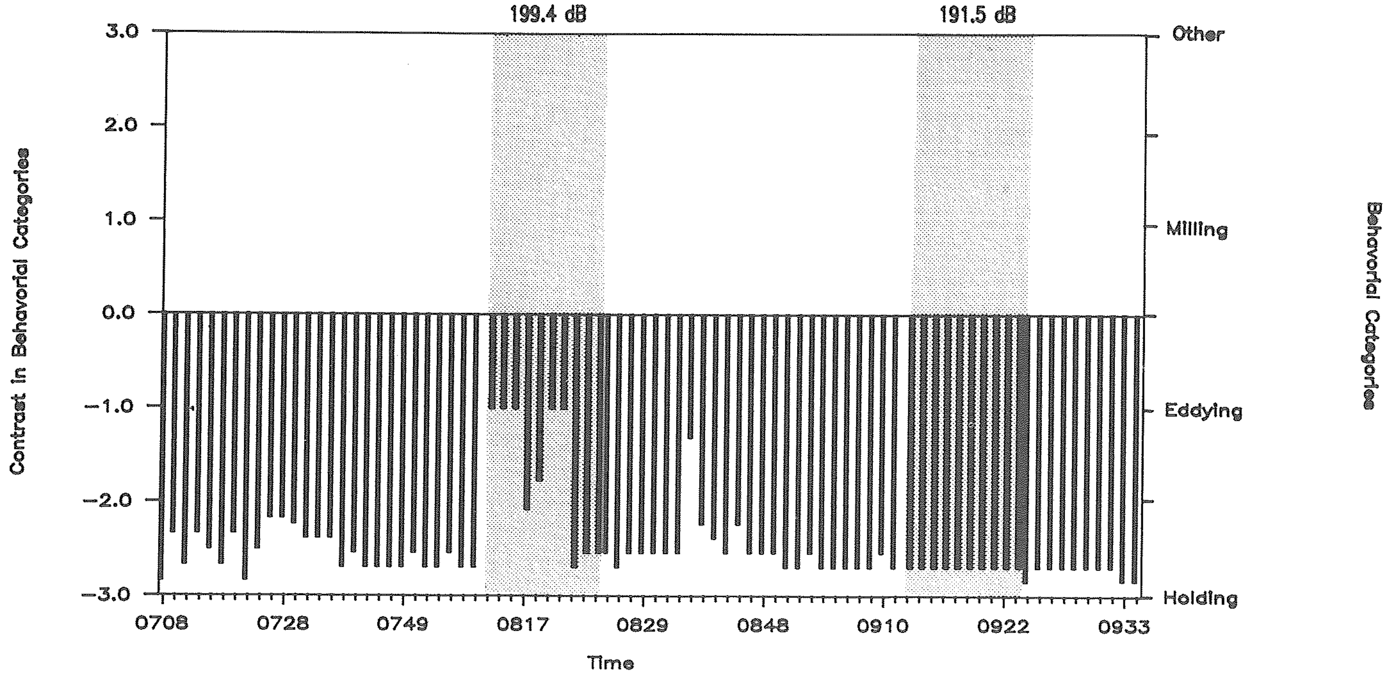

FIG. 10. Time sequence of behavioral patterns exhibited by rockfish in the enclosure as measured by linear contrast (3) for Trial 4.

(Keenleyside 1979), so that terming the changes in schooling behavior observed in blue and black rockfish an alarm response is supported somewhat by the ethological literature.

The threshold for startle responses was between 200 and 205 dB; however, because of the nature of the sound signatures at the enclosure, startle responses may be elicited at different levels or under limited circumstances during actual geophysical operations. At short range between the sound source and enclosure, the signature of the air-gun sounds had the abrupt character that Blaxter et al. (1981) considered most likely to elicit startle responses (Fig. 2). At longer ranges during the experiment (214 m; see Fig. 3), the sound levels were, of course, lower, but because of interaction with the sea surface, the sound signature had also changed character from abrupt to ramped. If an abrupt signature is necessary to elicit a startle response, then startle responses might occur at lower sound levels, when an

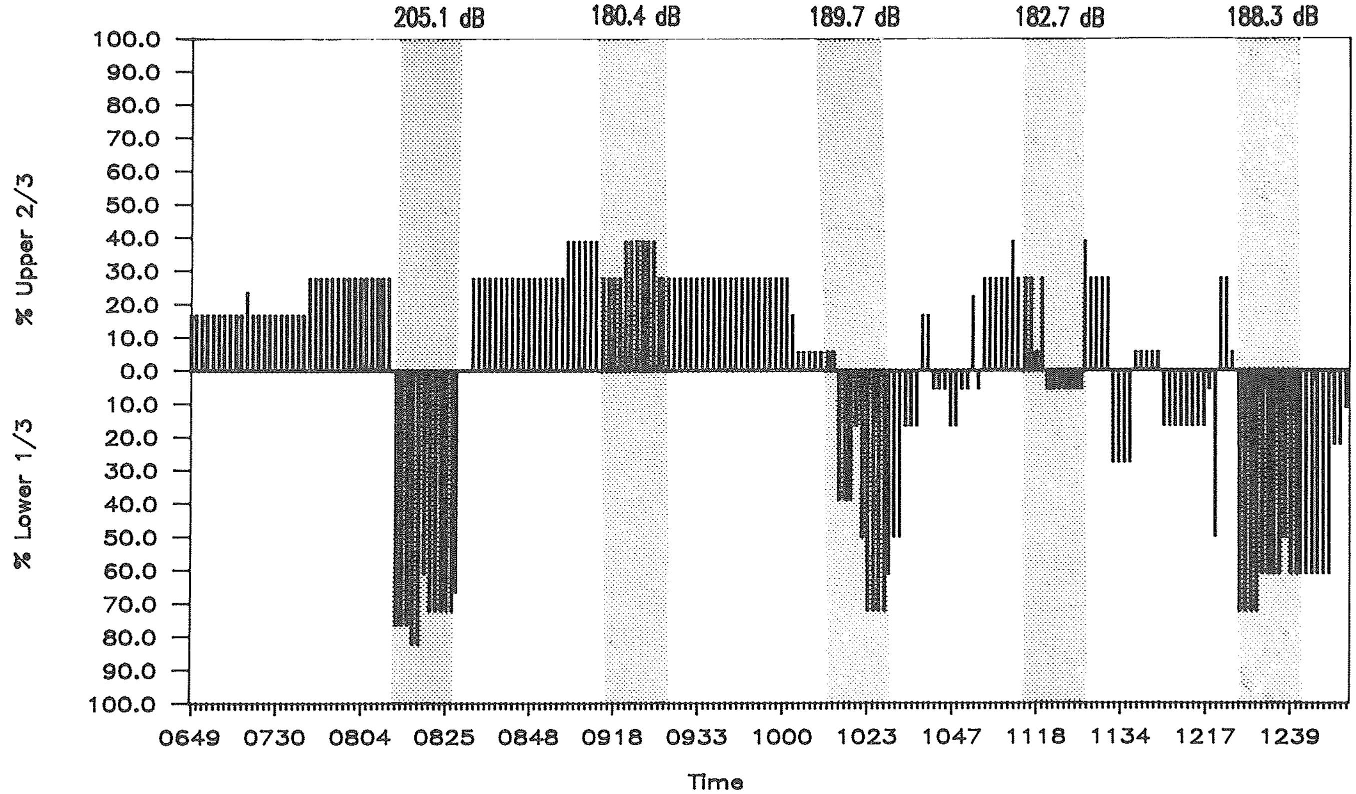

FIG. 11. Relative vertical position of rockfish in the water column of the enclosure per observation period during emission (shaded background) and nonemission (clear background) periods for Trial 5.

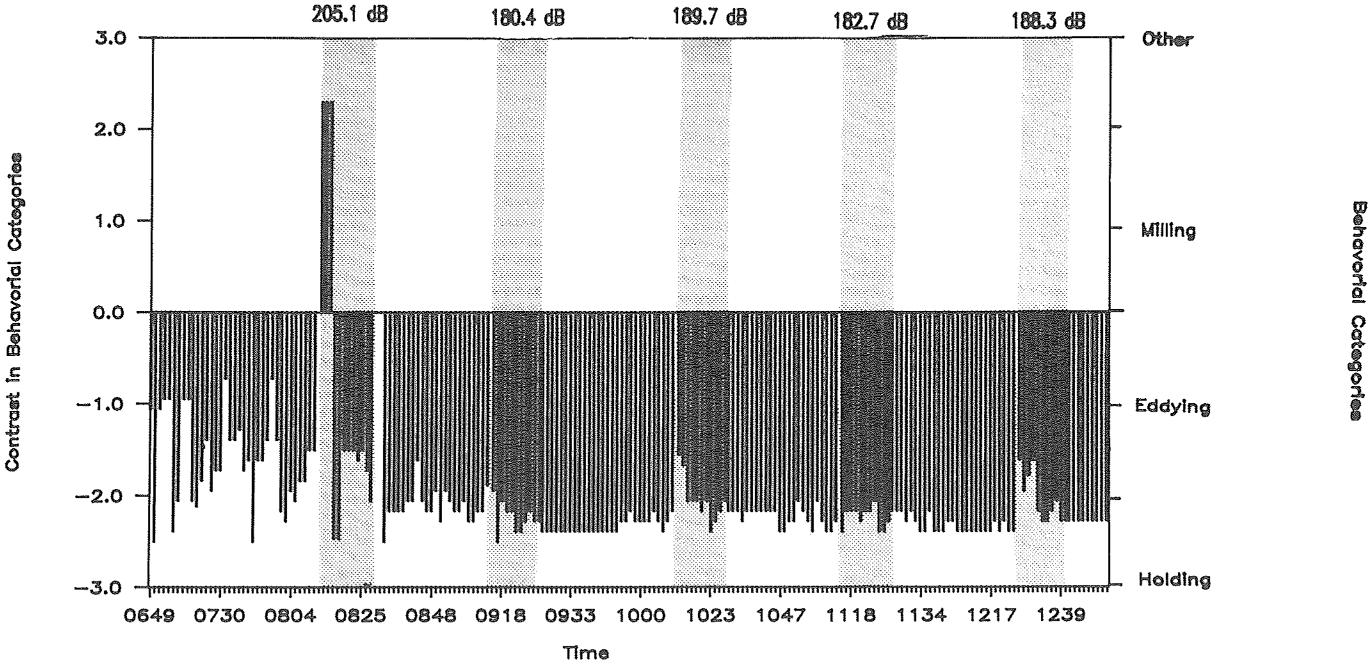

FIG. 12. Time sequence of behavioural patterns exhibited by rockfish in the enclosure as measured by linear contrast (3) for Trial 5.

abrupt signature is present, than we observed. Also, the acoustic signature of air-gun arrays presented by Malme et al. (1986) shows an instantaneous rise to maximum intensity when the receptor is on the beam axis. Off-axis sounds have the ramped pattern. Therefore, when survey vessels are running tracklines, the signature changes from ramped to abrupt and back to ramped as the vessel passes the point of interest. Under survey operations, then, the signatures most likely to elicit startle responses are present intermittently rather than continuously.

The data suggest the general threshold for alarm response to be about 180 dB. The regression analyses of the changes in depth distribution and the extent of active behaviors such as eddying and milling show that changes in these behaviors became more extensive as sound level increased. Extrapolation

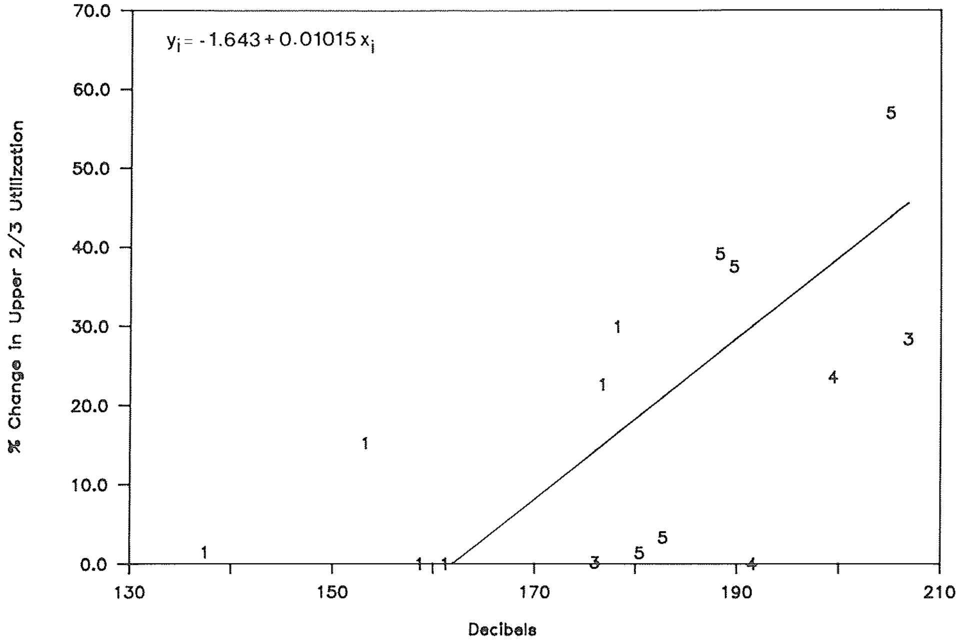

FIG. 13. Relationship between sound level (dB) of acoustic exposure and the percent shift in utilization of the upper two thirds of the enclosure (response variable (4)).

TABLE 3. Alarm (Al) and startle (St) response scores for captive rockfish presented with air-gun sounds. Sound levels are dB re 1 μPa. Response scores: 0, no response; 1/2, one or two fish respond; 1, several fish respond; 2, up to half the fish respond; 3, more than half the fish respond.

	Trial											
	1		2		3		4		5		Overall	
Sound level	Al	St	Al	St	Al	St	Al	St	Al	St	Al	St
207					3	3	3				3	3
205									3	3	3	3
199							3	0			3	0
195			2	0							2	0
192							0	0			0	0
190									3	1/2	3	1/2
188									3	0	3	0
186			1/2	0							1/2	0
183			0	0					1/2	0	1/2	0
180									1/2	0	1/2	0
178	3	0									3	0
177	1/2	0									1/2	0
176					0	0					0	0
161	0	0									0	0
159	0	0									0	0
155			0	0							0	0
153	0	0									0	0
137	0	0									0	0
No. of fish/ trial	20		3		13		13		15			

of these regressions suggests that more subtle changes in behavior could begin as low as 161 dB.

The general threshold of 180 dB observed here agrees well with some field observations of avoidance of air-gun sounds. Discharges of a single air gun with a source level of 220 dB have been reported to change the depth distribution of whiting (Chapman and Hawkins 1969). Using the echosounder of a vessel stationed over a school of whiting, these authors observed that upon discharge of an air gun, the whiting distributed between 27 and 55 m abruptly descended and formed a compact band just below 55 m. Assuming a transmission loss of 25 log(R), these findings suggest that the whiting avoided sound levels above 178 dB.

The thresholds observed here indicate that startle and alarm responses could be elicited by sounds from actual survey operations. For a typical air-gun array of 65 550 cm^3 with 32 guns and source level of 255 dB, the sound exposure from a trackline passing directly over a point at a depth of 100 m can be calculated from the sonar equation $S = \mathrm{SL} - 20 \log(R)$, where S = sound level at the point, SL = source level, which here is 255 dB, R = the range (metres), and 20 log(R) is the transmission loss. For a single trackline passing directly overhead and assuming a typical vessel speed (11 km/h) and array discharge rate (6 discharges/min), a point at 100-m depth would receive sounds with abrupt signatures and levels above 180 dB from approximately 1840 discharges over a period of about 5.1 h. Similarly, a point would receive sounds above 205 dB from approximately 103 discharges over about 17 min. With the array directly overhead, maximum sound level at 100-m depth would be 215 dB. For a transmission loss of 20 log(R), the distance from a 255-dB array where sound levels would be above the 205- and 180-dB thresholds for startle and alarm responses would be about 316 m and 5.6 km, respectively. For a transmission loss of 35 log(R), a value more typical of shallow water, the effective distances would be 1 m for startle responses and 139 m for alarm responses. For the coastal waters of California, transmission losses 20–25 log(R) have been observed. These calculations indicate that the conditions eliciting alarm responses are much more likely than those eliciting startle responses.

One aim of the behavioral experiment was to provide data to establish the sound exposure level in the subsequent fishing experiment (Pearson et al. 1987; Skalski et al. 1992). During this fishing experiment, sound levels at the bottom were always above 180 dB and often above 190 dB, so that the treatment level applied to the rockfish aggregations was within the range that produced the alarm responses observed here. The rockfish aggregations of the fishing experiment were probably rarely exposed to sound levels above 200 dB, the level at which startle responses were observed. The fishing experiment demonstrated a significant 52.4% reduction in catch-per-unit-effort (CPUE) in hook-and-line fishing targeted on rockfish aggregations under sounds from a single air gun producing the sound levels observed here to elicit alarm responss.

Results of the two experiments suggest that the reduction in CPUE was due to behavioral responses by rockfish to air-gun sounds. The sound levels during the fishing experiment were above those producing alarm responses but probably not above those producing startle responses. Echosounder transects of the rockfish aggregations before and during sound exposure showed that the height but not the area of the aggregation changed under sound exposure. This change in height but not area implies that the rockfish higher in the water column decreased depth to avoid the sound but did not disperse from pinnacle. Therefore, the sounds from the survey device appear to have acted mainly to reduce responsiveness to baited hooks.

While the likelihood of behavioral responses and reduced catchability is clear from the results here and in Skalski et al. (1992), how long reduced catchability might last was not addressed in our experimental design. The observation that rockfish returned to preexposure behaviors either late in the exposure period or within minutes after exposure ceased is evidence for habituation to the air-gun sounds. Because alarm and startle responses are usually not sustained long after removal of the effective stimulus, the reduced catchability can be expected to be transient. Other studies of different design are needed to know how transient any reduced catchability might be. Our study design did not address the effects of duration on the behavioral responses or catchability. In actual surveys, the survey vessel conducts 24-h/d operations for perhaps several weeks. Any other studies should include efforts to determine the influence of duration on the extent of effect and the time course of recovery.

Acknowledgements

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