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## Effects of seismic air guns on marine fish

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### Abstract

Observations of marine fish and invertebrates on an inshore reef were made using TV and acoustic tags one week before, during, and four days after a seismic triple G. airgun (three synchronised airguns, each gun 2.51 and 2000 psi) was deployed and repeatedly fired. The guns were fired once/min for eight periods on four days at different positions. The structure and intensity of the sound of each triple G. gun explosion was recorded and calibrated. Peak sound pressure levels of 210 dB (rel to 1  $\mu$ Pa) at 16 m range and 195 dB (rel to 1  $\mu$ Pa) at 109 m range were measured at positions where the fish were being observed. The final position of the triple G. gun, at 5.3 m range, had a peak pressure level of 218 dB (rel to 1  $\mu$ Pa). Neither the fish, nor the invertebrates, showed any signs of moving away from the reef. Firing the guns did not interrupt a diurnal rhythm of fish gathering at dusk and passing the TV camera position while the guns were firing. The long-term day-to-night movements of two tagged pollack were slightly changed by the arrival and banging of the guns particularly when positioned within 10 m of their normal living positions. Those reef fish, watched by the TV camera, always showed involuntary reactions in the form of a Mauthner cell reflex, C-start, at each explosion of the guns at all ranges tested (maximum range was 109 m, 195 dB rel to 1  $\mu$ Pa). When the explosion source was not visible to the fish, the C-start reaction was cut short and the fish continued with what they were doing before the stimulus. When the G. gun rack was sunk to the seabed (depth 14 m) visible to the fish and the TV camera, those fish that were observed approaching the G. gun rack when the guns were fired were seen to turn and flee from the very visible explosion. When the gun rack was suspended midwater (5 m depth) and just outside visible range at 16 metres, the fish receiving a 6 ms peak to peak, 206 dB (rel to 1  $\mu$ Pa) pressure swing exhibited a C-start and then continued to swim towards the gun position, their intended swimming track apparently unaltered. The sound of the G. guns had little effect on

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the day-to-day behaviour of the resident fish and invertebrates. Crown Copyright © 2001 Published by Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

Seismic surveys have been carried out at sea for many years in order to locate those geological structures that are associated with hydrocarbon deposits. High-energy sound sources are used to set up echoes in the earth, which are then recorded and analysed to determine the geological structure. Good echoes require precise, repeatable, short duration, high-energy pulses. Originally, these sources were explosive, using TNT or black powder. This practice has been discontinued owing to more stringent safety regulations and the fact that explosives can cause physical damage to marine animals (e.g. various papers in Greene et al., 1985). In recent years, many ingenious types of sound source have replaced chemical explosives in almost all cases and these include sleeve exploders, water guns, sparkers, boomers, vibroseis<sup>®</sup> and airguns. Reviews of marine seismic survey technology can be found in Kramer et al. (1968), Lugg (1979) and Johnston and Cain (1981). The commonest sound sources currently used for marine seismic surveys are airgun arrays but there are no standards and these can vary in design and size and output characteristics.

In water, the causes of injuries and death of exposed organisms were shown to depend upon two features of the sound source, a very high peak pressure and relatively short time for the pressure to rise and decay (Hubbs and Rechnitzer, 1952). According to Larson (1985) the death of adult organisms occurs when the peak pressure is greater than  $\sim 2.75 \times 10^5$  Pa (229 dB rel to 1  $\mu$ Pa), and the rise and decay time is less than  $\sim 1$  ms. Modern airguns generate pulses with a peak-to-peak time as long as 6 ms and there has been a general evolution towards sources that are not directly lethal to marine life. However, when a sound source with 6 ms peak-to-peak period is very close to an organism, the pressure may sweep through a damaging pressure change in any 1 ms period of the complete cycle. The rate of pressure change of one specific part of the cycle may be damaging at close quarters but become harmless at some distance as its amplitude is attenuated. Despite these earlier basic studies that showed the importance of the pulse timing together with amplitude, later studies have often failed to report the detailed measurements of the pulses used that are essential if we are to build on this knowledge. Turnpenny and Nedwell (1994) reviewed reported experiments on the effects of seismic survey sounds on aquatic life and the variable nature of the results are well presented in their Table 1. These authors point out a shortage of detailed information on the sources used and particularly the measured values for the timing and intensity of the pressure changes at the position of the organisms being tested.

Full-scale airgun arrays generate about 255 dB rel to 1  $\mu$ Pa at 1 m (231 at 16 m, 218 at 50 m) and drop to 201 dB rel to 1  $\mu$ Pa at 500 m. At 20 m the peak pressure is below the 229 dB threshold of Larson (1985) and with a 6 ms peak to peak pressure change, these levels are well clear of having lethal effects. Due to the long period of the pulse, dangerous rates of pressure change could be expected only within a few metres of an airgun array. The frequency of the pressure pulse falls in the most sensitive hearing frequencies of the fish. Cod, salmon, plaice and herring (Fig. 1) have

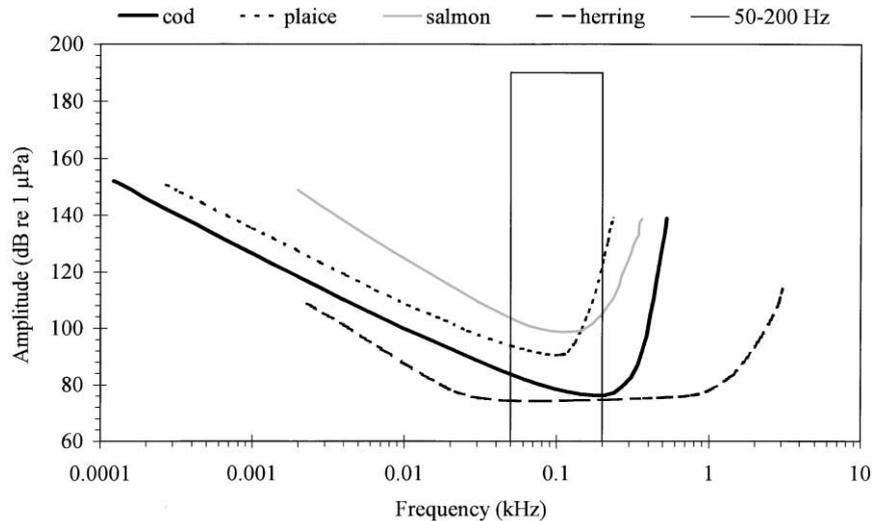


Fig. 1. Fish-hearing thresholds after Mitson (1995). The added block shows the frequency of the main peak to peak of the G. gun pulse being between 80 and 120 Hz and at the most sensitive point in the hearing of these four species. This hearing threshold level might reach as far as 100 km from a towed array in ideal transmission conditions (Greene and Richardson, 1988).

peak sensitivity at frequencies between 80 and 200 Hz with a sensitivity threshold at 80–100 dB rel to 1  $\mu$ Pa (Mitson, 1995). The high-intensity sound of an airgun array in ideal conditions might not fade below these fish-hearing thresholds even at 100 km distance (Greene and Richardson, 1988).

For these reasons, concern now centres more on the possible effects of these sources on the distribution, migration patterns and catchability of fish. There is therefore a need for information on exactly what effect such sound sources may have on the detailed behaviour patterns of fish at different ranges.

Several studies which reinforce this need are summarised by Turnpenny and Nedwell (1994) and by Gausland (1997). Recent studies using a number of methods to estimate fish distribution in open sea fisheries have been convincingly interpreted to suggest that gadoids leave the survey area during seismic surveys (Løkkeborg and Soldal, 1993; Engås et al., 1993, 1996). The change in distribution can lead to observations of catch increases in some areas and reductions in others (Løkkeborg, 1991). The areas apparently affected extended up to 33 km from the survey centre. Dalen and Raknes (1985) suggest that cod may swim towards the bottom and remain immobile during disturbance by sound and Løkkeborg and Soldal (1993) have used this change in behaviour to explain temporary increases in the catch rates of cod in saithe trawls during seismic activities. The assumed movements could be explained easily by swimming abilities, with larger fish moving further than smaller fish. Other studies such as the Poole Bay study (Pickett et al., 1994), showed no effect of seismic surveys on the distribution of tagged bass. Off California, Pearson et al. (1992) showed rock fish catches declined, mainly due to a change in fish depth rather than to dispersal of the shoals. Chapman and Hawkins (1969) illustrated, using an echo sounder, how whiting (*Gadidae*, *Merlangius merlangus*) in midwater schools moved deeper below an airgun fired while suspended from an anchored ship.

With this background the first question was, could we cause the fish occupying an inshore reef to move away from the reef by approaching it with an airgun as used in surveys. Secondly, could we set up a range of observation techniques that would illustrate the behaviour of the inhabitants of the reef when the gun was fired. For many years, the behaviour of the fish inhabiting an underwater reef 'Fish Rock' in Firemore Bay, Loch Ewe, on the west coast of Scotland, has been studied initially by diving (Wyche, 1984) and later by acoustic tracking using a fixed hydrophone array (Johnstone et al., 1991; Glass et al., 1992; Sarno et al., 1994). Fish inhabiting this reef include juvenile saithe (*Pollachius virens*) that leave for the open sea when they are 2–3 years of age at a length of 40 cm, adult pollack (*Pollachius pollachius*) up to length 70 cm or more, juvenile cod (*Gadus morhua*) and occasional visits by adult mackerel (*Scomber scombrus*), with some flatfish, wrasse, gobies, dogfish and skate. Saithe move about Fish Rock in schools making occasional forays over the sand away from the reef during the day (Sarno et al., 1994). Pollack behaviour is size dependent with smaller fish behaving in a similar way to saithe while large adult fish are more solitary and territorial and spend all their time patrolling between the *Laminaria* fronds that grow in abundance on the rocky reef. This knowledge of the day-to-day distribution and behaviour allowed us to set up various means of efficiently observing the fish at key points around Fish Rock and investigate the effect on them of firing near them a triple G. airgun.

## 2. Materials and methods

### 2.1. Study site

Firemore Bay in Loch Ewe (Fig. 2) has a Marine Laboratory field station close (400 m) to an isolated underwater reef (Fish Rock, Fig. 2) in the bay. The proximity to the shore station allows the practical laying of cables servicing equipment like TV camera, sonar scanner and hydrophones. Fish Rock has a well-studied resident population of gadoid and other fish species of a variety of sizes. The reef rises about 7 m above the surrounding sandy seabed and is covered in *Laminaria* spp. The bay is sheltered from the westerly wind but exposed to northerly gales with a clear fetch through the mouth of Loch Ewe to the Minch. The site deepens from 10 m below MLWS towards 20 m below MLWS over a 300 m band (Fig. 2).

### 2.2. Seismic sound source

The seismic survey equipment consisted of a rack containing three synchronised 150 in<sup>3</sup> (2458 l) pneumatic, recoilless sleeve guns, G. guns (Seismic Systems Inc and Soderia). Each G. gun weighs 56 kg and has overall dimensions of 60 cm length and 29 cm diameter. The G. guns represent a type of gun now commonly used by survey companies in arrays and clusters for survey work. They also are the only safe type of gun to manhandle from a small boat because they are recoilless and can be submerged while uncharged with gas. The rack containing the G. guns was suspended at a depth of 5 m from a large plastic float and portable anchor. Once deployed the G. guns were charged remotely from the shore via a 400 m long hose pipe using nitrogen quads operating at 2000 psi. The three guns were simultaneously fired with a radio-linked detonator housed in a

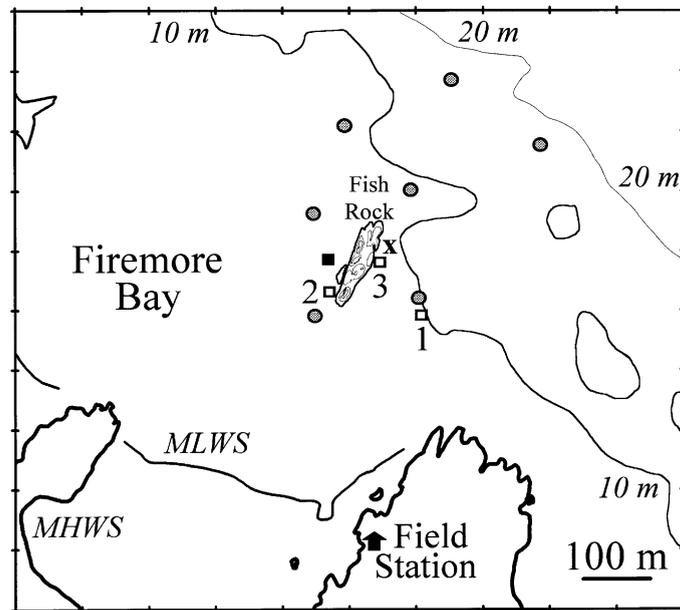


Fig. 2. Map of the study site at Firemore Bay, Loch Ewe, on the west coast of Scotland. The mean high-water spring (MHWS), mean low-water spring (MLWS), 10 and 20 m depth contours are marked. For gun position dates and firing times see (Table 2). The small black square marks the reference point from which the fish movement distances are measured in Figs. 7 and 8. Open squares mark the G. gun positions, grey circles mark the hydrophone positions and the X marks the location of the TV camera.

zodiac inflatable boat moored alongside the G. guns. The remote controlled firing encoder (Input/Output Inc., ENC-230BJ1) operated from the shore observation station. The firing of the three guns was electronically synchronised to less than 1 ms. The positions and firing periods for the G. guns are identified and summarised in Fig. 2 and Table 2.

### 2.3. Underwater sound measurement

It is difficult to predict the characteristics of the sound propagation in a shallow water area such as Firemore Bay, so careful measurements were made to check the characteristics of the sound received by the fish at different distances from the gun positions. Sounds were recorded at measured distances (16–206 m) from the source using a calibrated hydrophone (Brüel and Kjær, 8100) with a precision conditioning amplifier (Brüel and Kjær, type 2650), connected to digital audio tape (DAT) recorders (Casio DA-1 and DA-2). The recording equipment was carried in a zodiac-inflatable boat drifting passively down wind from the mooring buoy from which the gun rack was suspended. The distance of the hydrophone from the source was set using a tight, floating, graduated line fixed to this mooring buoy. The hydrophone mounted in a rigid frame was lowered to the same depth as the gun rack at 5 m depth. At different ranges the calibration of the recorded signal amplitude was maintained by using only known calibrated positions of the adjustable settings of the precision conditioning amplifier and DAT recorders. Recorded sounds showing no saturation were later analysed using Loughborough Sound Systems speech

Table 1  
Fish tagged with identification letter and duration of tracking

		Length (mm)	Start		Finish		Duration (h)
			Date	Time	Date	Time	
A	Cod	320	7 August 1997	21:38	16 08 97	23:00	217.4
B	Pollack	360	8 August 1997	17:00	16 08 97	09:00	184.0
C	Saithe	300	8 August 1997	21:22	—	—	~2
D	Pollack	360	8 August 1997	21:40	26 08 97	11:00	421.3
E	Pollack	510	11 August 1997	22:10	26 08 97	10:00	347.8

Table 2

Triple G. gun firing protocol for the experimental period 19–23 August 1997. The locations D1–3, refer to the gun positions marked in Fig. 2. The gun was usually fired every 60 s and the number of shots are shown for each firing session. The range to the TV camera from the gun rack is in metres and the sound pressure level (SPL) at the TV camera in dB (rel to 1  $\mu$ Pa)

Event	Date August 1998	Start time (h/m)	Stop time (h/m)	No. of shots (no.)	TV range (m)	SPL at TV (dB)	Recorded bangs (no.)
Deploy (D1)	19	10:10					
F1	19	21:10	21:35	8	109	195	
F2	20	11:01	12:01	60	109	195	
F3	20	20:59	21:33	20	109	195	
F4	21	12:20	12:53	34	109	195	16
F5	21	13:17	13:34	18	109	195	18
Move to (D2)	21	15:00			90	200	
F6	21	20:26	21:40	74	90		
Move to (D3)	22	12:50					
F7	22	15:54	17:20	43	16	210	43
F8	22	20:30	21:10	38	5.3	218	
Remove gun	23	10:30					

workstation software and Cambridge Electronic Design Spike 2 software. Fast Fourier transforms were carried out on spreadsheet values, generated from selected recordings, by Spike 2 software (Cambridge Electronic Design).

#### 2.4. The tagged fish

Fish were caught using rod and line with barbless hooks on and around Fish Rock during the period 7–11 August 1997 and five fish selected for tagging. Each of the selected fish was measured, an acoustic “pinger” was attached externally (Table 1) and the fish was then immediately released at the capture site.

The acoustic tags (HS Electronics) were designed and developed by the Ministry of Agriculture, Fisheries and Food, CEFAS, Fisheries Laboratory, Lowestoft. They are cylindrical in shape (51 mm long and 16 mm in diameter) and weighed 14.9 g in air and 5.3 g in water. Each tag

transmitted once/s a pulse lasting 2 ms at a unique frequency. The five fish were identified with unique frequencies between 72 and 84 kHz. The duration of tracking depends on tag retention time and the maximum battery life which is 28 days (bench test) when transmitting once/s.

### *2.5. Tracking the tagged fish positions*

The positions of the five fish were continuously updated using a computer linked to a fixed array of seven hydrophones (Urquhart and Smith, 1992), which was deployed on 5 and 6 August 1997. The seven hydrophones, each linked to the shore by a cable, were anchored about 100 m apart to form an array of listening stations around the underwater reef (Fig. 2). The position plotting involves the signal of a particular tag being received through at least three of the seven hydrophones and its relative timing at each hydrophone analysed by an Essex Electronics “Chameleon” single board computer and sent onto a BBC Master 128 PC. A custom-written computer programme then uses the time differences of at least three selected hydrophone signals to give a position fix for the tag using hyperbolic functions. Fish were each tracked for 30 s, and for each 30-s track a single “average” coordinate was calculated, after outlying points had been removed. For each of the tracking positions, the computer programme calculated the Cartesian coordinates of the position and converted this position to UK National Grid coordinates, based upon hydrophone positions calculated from distances measured from a reference point using a laser range finder (Impulse XL, made by Laser Technology Inc.).

Errors associated with the tracking system have been discussed in Urquhart and Smith (1992), Maclellan and Hawkins (1977) and Hawkins and Urquhart (1983). Errors were reduced by using a data reduction method, removing outliers based upon maximum fish swimming speeds and statistical measures of variation, and calculating a single “average” position for a fixed time interval (after Urquhart and Smith, 1992). The mean coordinate pair was calculated, along with 95% confidence limits, for every 30 s of data. All fixes outwith the 95% confidence limits were then rejected and the average recalculated. This procedure was repeated until no position fixes were rejected. In the context of this study the resultant 30-s “average” position was used for all data analysis and figures.

### *2.6. Underwater television observations*

On 6 August, an underwater television camera (Osprey RF SIT Camera OE 1321, OE 1231A power supply), together with a floodlight mounted on a pan and tilt assembly, was positioned on the sea bed at the north-east edge of the Fish Rock (see TV, Fig. 2). A cable linked this assembly to the shore laboratory. Real-time and time-lapse video recordings could be made using a time-lapse video recorder (Panasonic S-VHS TLVCR AG6730), and still pictures were printed using a video graphic printer (Sony UP-811). A broad band hydrophone (ITC-6050c), for monitoring background sound, and a scanning sonar (SIMRAD Mesotech MS971), for observing the G. gun firings, were deployed near the TV camera. From 11 to 24 August a continuous time-lapse recording (48 h periods were recorded on a 3-h tape, one frame per second), was made in order to monitor animal movements and abundance. During airgun firings the video recorder was switched from time-lapse to real-time in order to observe the details of animal reactions to the seismic sounds.

The time-lapse video tapes were analysed later to give values for both animal abundance and their activity when within the field of view of the TV camera. A relative index of fish abundance was used in order to compensate for variations in quality of recordings and water visibility. The numbers of animals in the field of view were recorded in 30-min blocks. Animals were classified as small gadoid (<300 mm), medium gadoid (300–500 mm) or large gadoid (>500 mm); other fish observed included gobies, flatfish and wrasse. The invertebrates included crustaceans, echinoderms and molluscs. The numbers of fish observed in the field of view, for the three gadoid groups, were recorded as one fish, two to 10 fish or >10 fish. An index of abundance was calculated by adding the numbers observed together after multiplying the three group sizes by one, five and 20, respectively.

### 3. Results

#### 3.1. Seismic sound characteristics

The triple G. gun rack was deployed at location 1 (Fig. 2) at 10:10 h on 19 August. The timing and duration of each firing period are shown in (Table 2), with the number of shots fired.

On three occasions calibrated DAT recordings were made. Sixteen bangs were recorded at 118 m (Event F4, Table 2), 18 bangs at 62 m (Event F5) and 43 bangs at varying distances (Event F7). The waveforms recorded at different distances from the G. guns are shown in Fig. 4. The amplitude of the sounds produced by the synchronised firing of the three G. guns was calculated from the recordings during Event F7 and is shown in Fig. 3. The amplitude of the initial peak

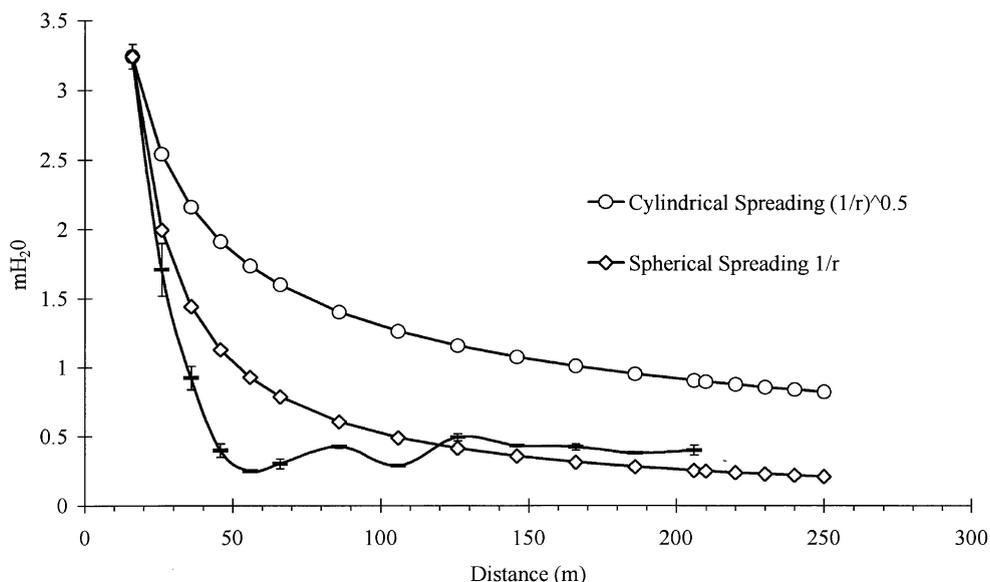


Fig. 3. Amplitude of sound generated by the three G. guns (mean  $\pm$  SD) plotted against distance. The included lines show the expected drop in amplitude for cylindrical (top) and spherical (bottom) spreading. Each y-axis division of pressure represents 0.5 m of water or 5000 Pa.

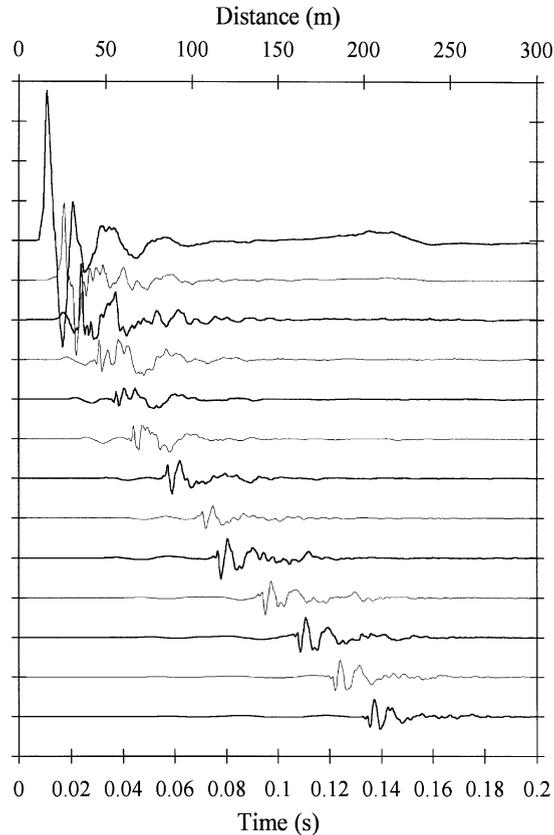
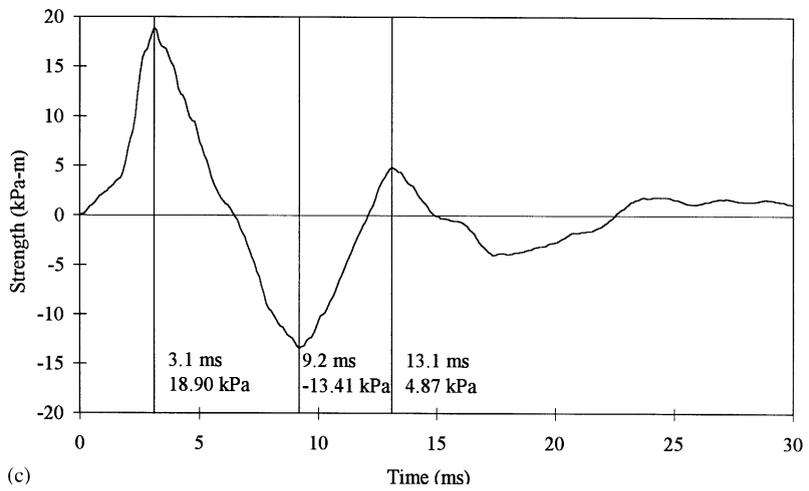
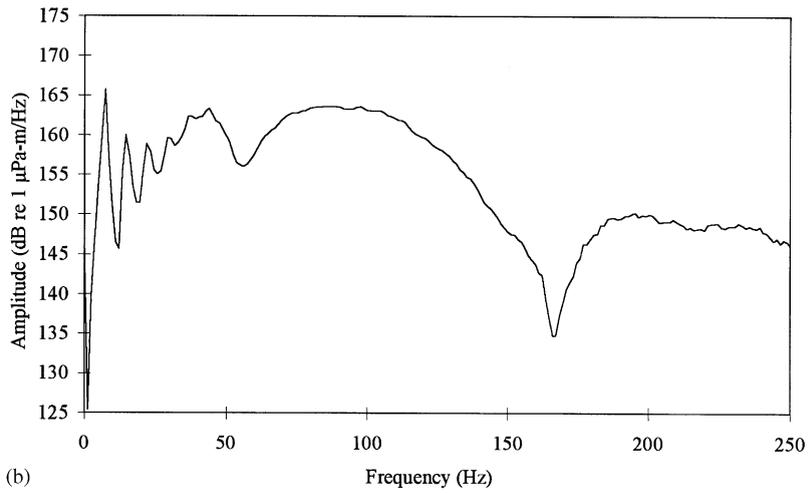
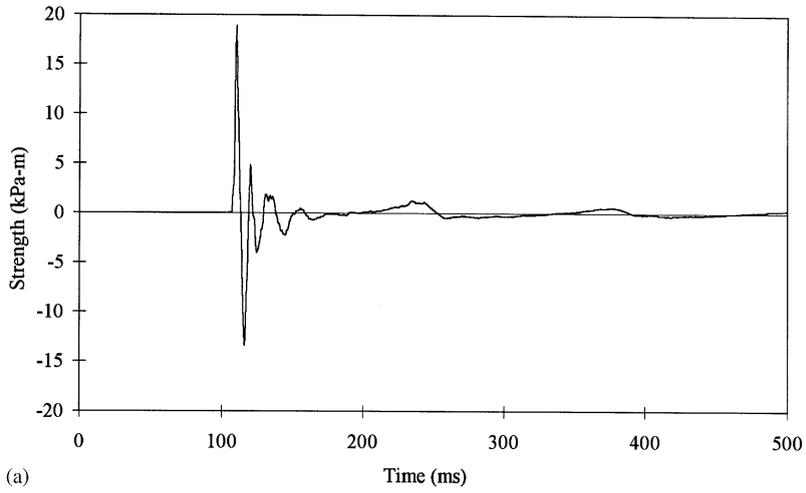


Fig. 4. Relative amplitude records of the bangs of the triple G. guns recorded at different distances marked as distance and time on the *X*-axis. Each *y*-axis division of pressure represents 0.5 m of water or 5000 Pa, with the graphs staggered on the *y*-axis for ease of comparison.

pressure wave of the sound drops off from 206 dB (rel to 1  $\mu$ Pa) at 16 m to 190 dB (rel to 1  $\mu$ Pa) at 206 m. These pressure waves are equivalent to a 3.1 m depth change of water and a 0.31 m depth change at ranges of 16 and 206 m, respectively. The signature and spectrum of sound from the triple G. guns, measured at 16 m, are shown in Figs. 5a and b. The sharp drop in amplitude over the first 50 m of distance from the gun can clearly be seen, as well as the fact that from 50 to 200 m there is little change in amplitude, with interference effects, both constructive and destructive, visible. From 50 to 200 m the waveforms all have a similar shape.

### 3.2. Fish tracking

Of the five fish which were tracked for periods of up to 18 days, (421.3 h, Table 1) only two pollack remained close enough to the study area to give continuous positions that revealed possible reactions to the guns. Fig. 6 shows examples of the mapped day/night positions of pollack D and pollack E for a typical 24 h period before the deployment of the guns. Figs. 7 and 8



show alternative presentation of these positions and how they varied from day to day for the whole study period as a plot of the distance of each fish from the fixed reference point (black square in Fig. 6). For the nine days before arrival of the boat deploying the gun, pollack D showed a regular day/night pattern (9/8–18/8, Fig. 7) similar to that seen in Fig. 6, i.e. the fish moved out to the smaller reef 150 m north-east of Fish Rock every morning, and moved back to Fish Rock every evening. This behaviour pattern changed on 19 August when the fish failed to move out to the smaller reef as expected. This change in behaviour coincided with the arrival of the charter vessel *Patty Anne* (12 m, 130 HP, single prop.) to deploy the G. gun rack (Fig. 7, event D1). The position of Fish D showed little variation at the onset of, and during, G. gun firings, never being closer than 35 m from the G. guns. During the night of 19 August the fish moved to the west of Fish Rock and stayed there until 23 August when lack of movement of the fish (Fig. 7) indicated the tag had probably been shed.

Fish E never left Fish Rock at any time after release on 11 August. By 15 August the fish had settled down to moving between two areas on either side of the reef, in a fairly regular manner (see example Fig. 6b). This daily behaviour pattern is plotted, in Fig. 8, as distance from the reference point (black square, Figs. 2 and 6) and shows some detailed reactions to the gun when it is brought close to the fish on 22 August and fired event F7. Details of pollack E reacting to event F7 are expanded in Fig. 9 where position is plotted in relation to distance from the gun, and in

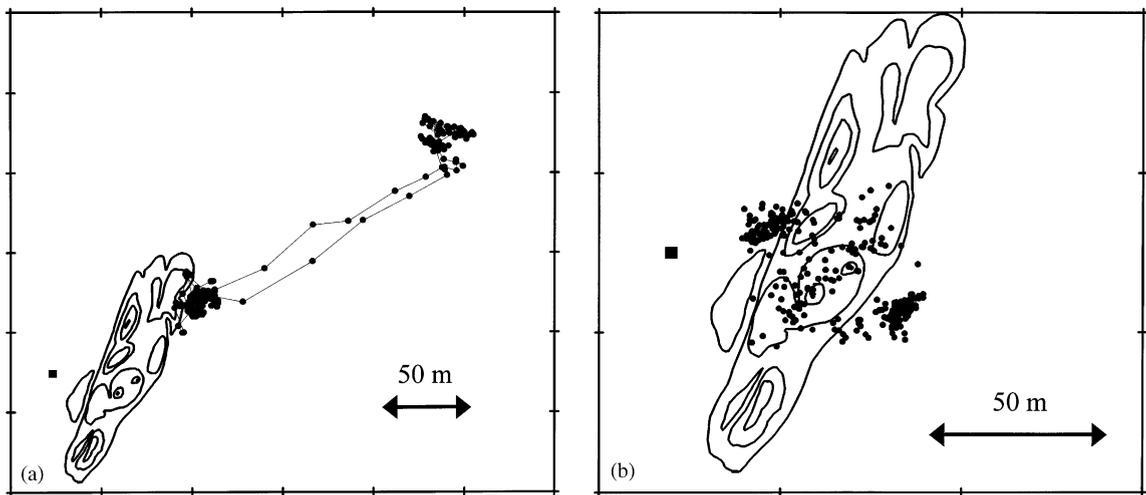


Fig. 6. Positions of tagged, tracked pollack during one 24 h period superimposed on a map of Fish Rock. Each data point is the average of 30 fixes recorded over one minute with any outliers removed (see methods). (a) Pollack D during 17 August 1997. (b) Pollack E during 15 August 1997.

Fig. 5. (a) Time amplitude signature of the triple G. guns recorded at 16 m from the guns. Each y-axis division of pressure represents 0.5 m of water or 5000 Pa. (b) Spectrum of the sound signature in Fig. 5a, calculated using fast Fourier transform of 8000 points in 0.8 s. (c) Details of the first 30 ms of the sound signature in Fig. 5a showing the timings and amplitude of the first three peaks. The average frequency, for peaks 1–3, is 100.1 Hz.

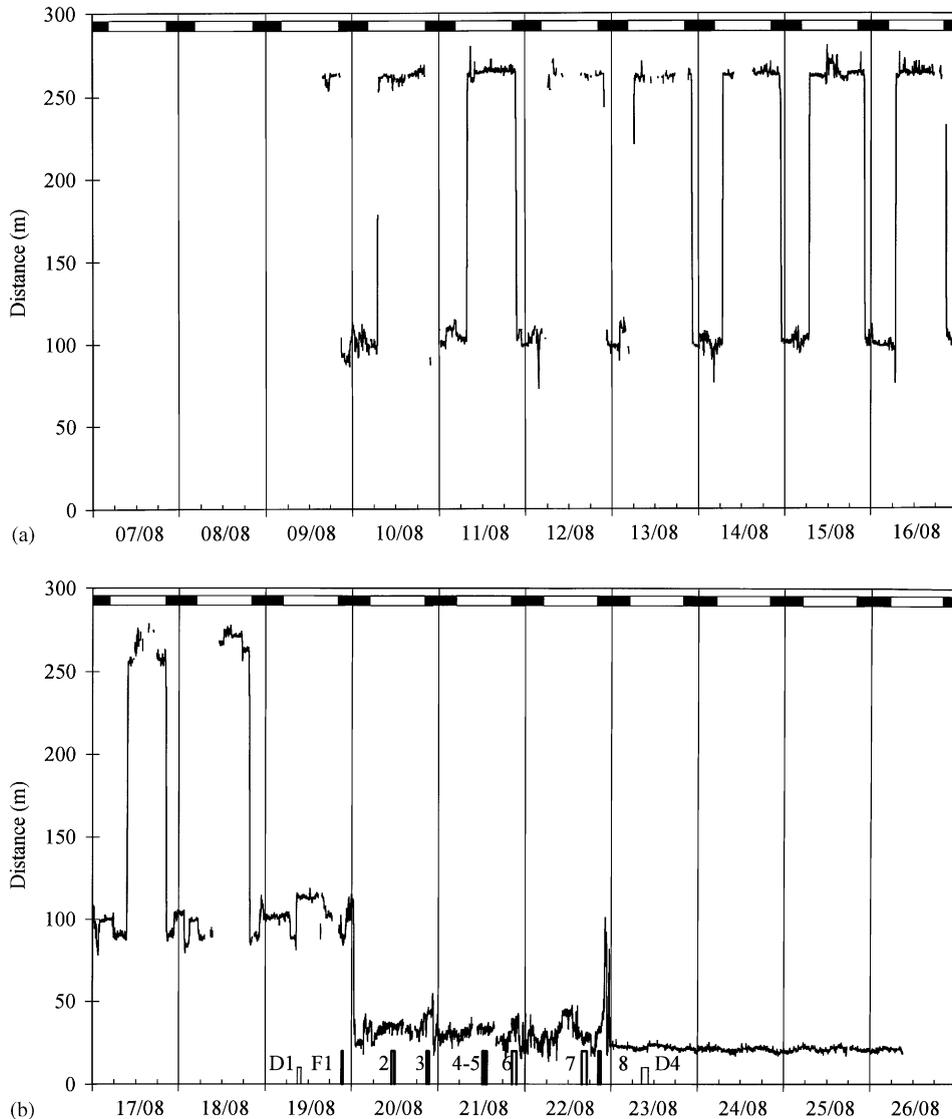


Fig. 7. (a) and (b). Distances of tagged pollack D from the reference point marked as filled square in Figs. 2 and 6. The bar at the top of the figure shows the daylight to dark timings, based on civil twilight at the site. Timings and durations of disturbances (for boat and seismic sounds see Table 2) are indicated with vertical bars. Gaps indicate loss of the tag signal.

Fig. 10 where the movements during the 43 min of the gun firing (event F7) are plotted every 60 s as a map.

At the onset of event F7, fish E was  $\sim 10$  m from the G. gun location, and after the first firing the fish moved rapidly away from the gun by  $\sim 30$  m. Similarly, the arrival of the boat on 23 August caused the fish to move away from the G. gun position (Fig. 9). Contact was lost with the tag on 26 August although the day-to-night movements across the reef were beginning to show again.

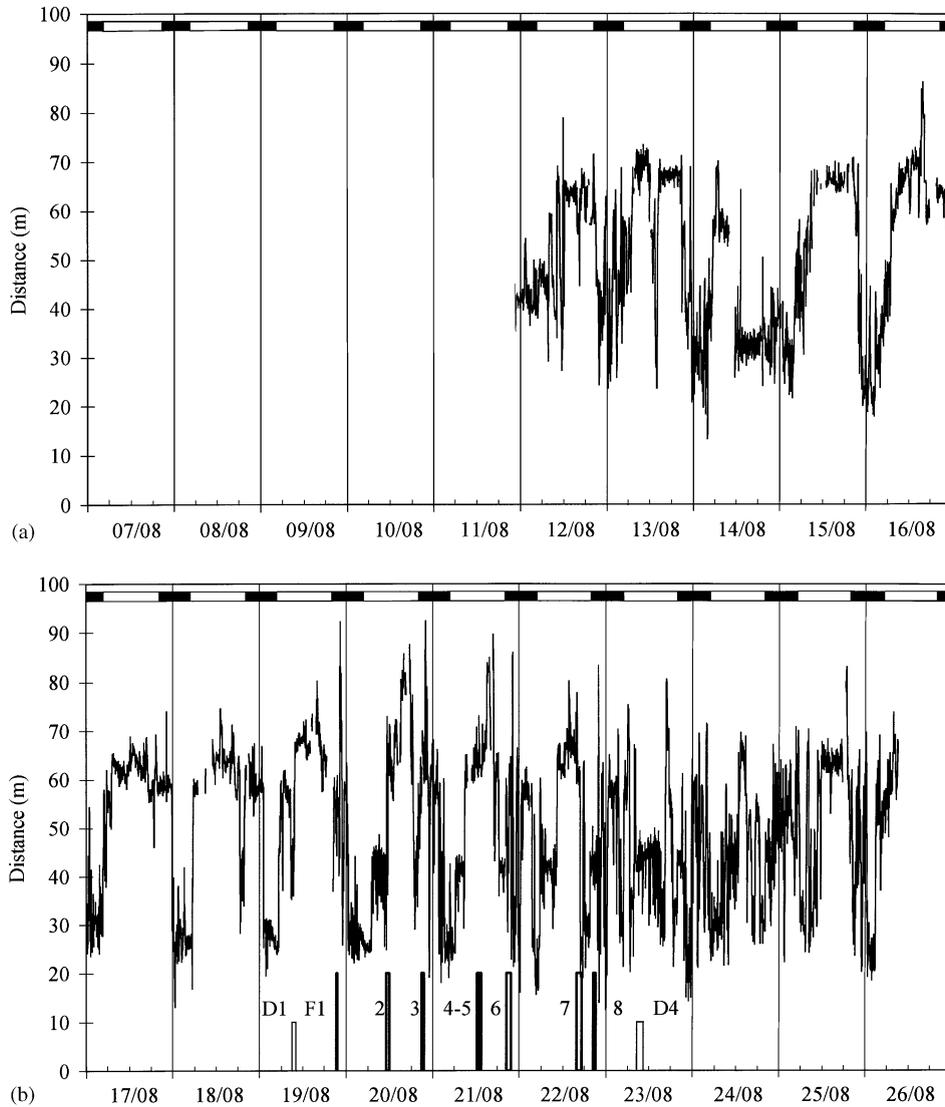


Fig. 8. (a) and (b). Distances of the tagged pollack E from the reference point marked as filled square in Figs. 2 and 6. Otherwise as Fig. 7. Loss of signal, on 14 August, coincides with the observation of a seal hunting on the reef and fish probably sheltering.

### 3.3. Underwater television observations

Between 10 and 19 August, before the G. guns arrived, a one frame/s, time-lapse, recording showed the species present and their activities (apart from hours of darkness). During the sessions of repeated gun firings, listed in Table 2, the reactions and activity were captured in real-time with 50 frames/s recordings. Periods between firing sessions and after the guns were removed were recorded at one frame/s. Altogether, 11 three-h video tapes covered the whole period of the

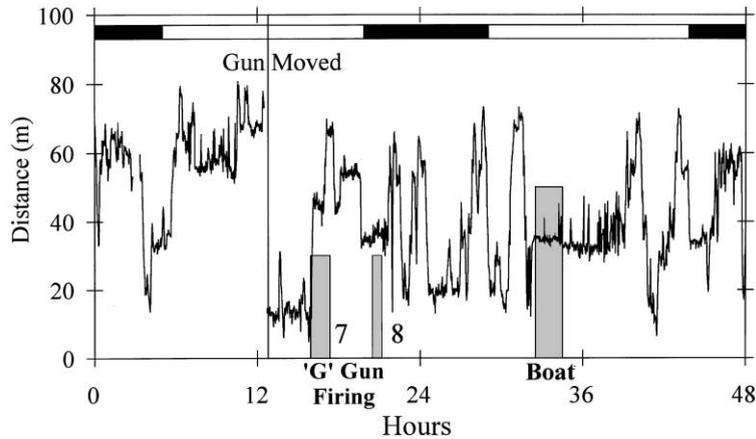


Fig. 9. Distances of the tracked pollack E from the G. gun position during the course of the G. gun firings, 22–23 August, plotted against time. The change from gun positions 2–3 (see Fig. 2) is marked by the vertical line. Events F7 and F8 are shown and the final retrieval of the gun rack by the boat (see Table 2).

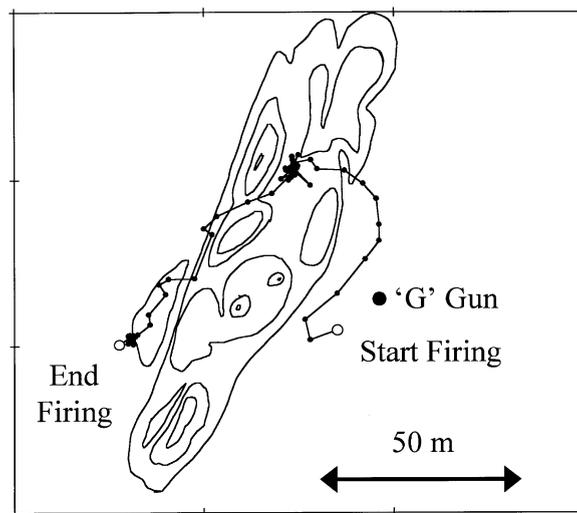


Fig. 10. A map showing the change in position of Pollack E as it moved over Fish Rock during the gun firing event F7 (see Table 2 and Fig. 9). Plotted points are 60 s averages over 43 min.

experiment. These tapes were analysed to give values for animal abundance and activity within the field of view of the TV camera before, during and after the guns were fired.

Fig. 11a shows the numbers for small, medium and large gadoids, counted during 30-min intervals. Some shoals of small and medium gadoids contained in excess of 50 individuals so that the numbers counted are probably an underestimate of actual animal numbers, except in the case of large gadoids which were not observed shoaling. The numbers of other fish (gobies, flatfish and wrasse) and invertebrates observed every 30 min are shown in Fig. 11b. The numbers of gadoids observed, especially for medium and small gadoids, show definite peaks of abundance at dawn

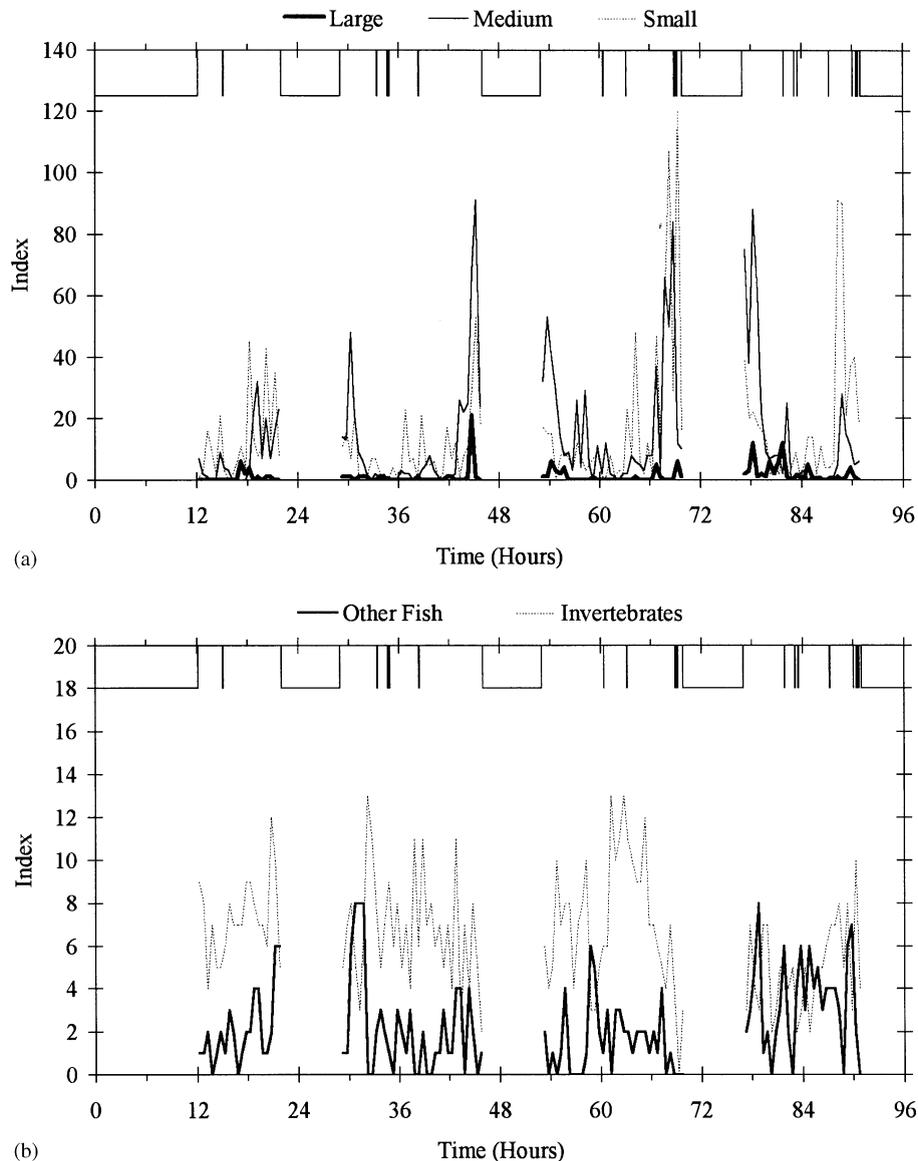


Fig. 11. The two graphs plot the number of animals present counted in the time lapse TV camera recordings. The blocks indicate the timing and duration of missing data due to either darkness or movement of the camera. (a) Number of gadoids within the field of view of the underwater camera, recorded on time-lapse video. The numbers were recorded in 30-min bins, with gadoids observed recorded as small, medium or large. Group size was recorded as 1, 2–10 and > 10. Actual numbers observed were multiplied by factors depending on group size: 1 (\*1), 2–10 (\*5) and > 10 (\*20) and added together to give an index of abundance. The gaps in the traces are periods of missing data during darkness and camera movements. (b) Number of non-gadoid fish and invertebrates within the field of view of the underwater camera, recorded on time-lapse video. The numbers were recorded in 30-min bins. Non-gadoid fish include gobies, flatfish and wrasse. Invertebrates include crustaceans, echinoderms and molluscs.

and dusk. No observations were made during the night so that there is no indication of how long the peaks in abundance lasted. There is little variation during daylight hours in the numbers of invertebrates and small fish (Fig. 11b).

From 10 August, when the TV camera was first installed, on each evening towards dusk large numbers of gadoids, saithe, whiting and small cod swam past the camera along the sea bed bordering the reef. This behaviour continued for about an hour until it was too dark to observe. On four evenings from 19 to 22 August the triple G. gun was repeatedly fired through the period of dusk and as the fish passed the TV camera (Events F1, F3, F6 and F8, Table 2). On 19th and 20th the distance of the gun array from the TV camera was 109.5 m (D1, Table 2). On 21st it was 90.4 m away (D2, Table 2) and on 22nd was first at 16 m (D3, Table 2) and then could be seen by the TV camera at 5.3 m distance. The video tape recordings have the sound of the guns firing recorded on the sound track and the fish, observed at the firing time, show a reflex skip to one side and then continue swimming in their original direction. On the evening of the 21st the gun rack was positioned so that the fish passing the camera were swimming directly towards it, still invisible 90.4 m ahead of them. The guns were fired as the fish were passing into the field of view of the TV camera, and they were seen to side skip and continue swimming directly towards the gun. Fig. 12 shows a closer view of saithe responding to the gun firing in event F7. On the 22nd, the gun rack was sunk to the seabed (about 14 m depth) and positioned so that it was visible ahead of the fish as they passed the TV camera. The first firing of the guns when on the seabed involved a TV view of many fish swimming from the camera towards the guns when they were fired. All these fish were seen to skip and then turn away from the very visible explosion, swimming back towards and past the TV camera. It was estimated that some of these fish came from a point within 1.5 m of the gun rack. The seabed, at this point, was composed of fine sand and the firing of the G. guns caused a major visual stimulus for the fish as a mushroom-shaped sand cloud was suddenly formed under the rising air bubbles. Then the base of the cloud spread outwards from the explosion finally obscuring the TV view.

The evening following the last G. gun firing, TV observations showed the fish patrolling the reef as they had on previous evenings. Previous studies at the same reef, including individually tagged fish, had indicated that the same fish returned to patrol the reef every evening, for up to two years (Sarno et al., 1994; Glass et al., 1992; Wyche, 1984). Their results led us to assume that the fish observed each evening for 14 days before, during and after the gun firings, were the same individuals following a daily routine and not new arrivals to the reef from other areas.

### 3.4. Other observations

At 11:10 h on 14 August 1997 acoustic signals from the fish tags could not be detected (see gap in records Figs. 7 and 8). Signals can be attenuated or obscured if a fish moves to the bottom or into weeds or rocks. At ~11:20 h one of the researchers (CSW) observed, from the shore, a seal on the water surface over the reef. Subsequent analysis of the underwater time-lapse video footage showed both fleeing pollack and other fish and a grey seal (*Halichoerus grypus*) swimming close to the TV camera by the reef (11:21:05–11:22:12). The seal approached from above in the camera view and then swam directly at the camera from the reef. After a few seconds moving around the base of the TV camera mountings, the seal lay on the seabed directly in front of the camera and remained there for 30 s before swimming away. It is likely that the presence of the seal



Fig. 12. Images from video tape of three saithe showing the bang-induced side skip or C-start. All three saithe show the reaction in the same TV frame (Frame 2). Note the sound pulse, lasting 6 ms, travels 30 m during one TV frame of 20 ms and the visual range is about 6 m. The first three images are 20 ms apart, the fourth frame is 5 s later, showing the saithe continuing to swim towards the gun. Recorded during event F7 (Table 2).

caused the loss of the fish-tracking signals, all of which had become loud and clear again 30 min later. It is, however, not clear by what mechanism the fish appeared to almost simultaneously react to the presence of a seal in the vicinity of Fish Rock. This form of behaviour, moving into cover when disturbed, was not observed for the two fish being tracked at any time during the course of the airgun firings.

## 4. Discussion

### 4.1. *Bangs did NOT chase fish away*

The regular daily pattern of schooling fish was seen and recorded by the TV camera for more than a week. Similarly the two tagged pollack showed repeatable day/night movements. On 19 August the triple G. gun was deployed 109 m from the camera and prepared for firing. Observations made during firing of the guns (see events F1–F5, Table 2) showed that the only obvious effect was that all the fish gave a C-start at each bang of the gun but continued as before. The C-start is an involuntary sudden bending of the body, see below for details. There was no movement of the fish or the invertebrates away from the gun. The gun was moved nearer until the fish were seen between the TV camera and the gun and only then when the explosion was visible to the fish did the fish react directionally to the gun. A peak pressure change of 218 dB (rel to 1  $\mu$ Pa), or 0.79 bar, was measured at a range of 5.3 m but in this last filmed observation of the gun, the fish swam from a point within 1.5 m of the gun rack towards the camera 5.3 m from the gun rack apparently undamaged. The peak pressure at 1.5 m is close to 229 dB (rel to 1  $\mu$ Pa), or 2.75 bar, with a 3 ms risetime. An equivalent pressure and rise time would be received at about 20 m below a survey array of 30 of these airguns. Nearer than this, the sound radiating from each of the widely spread individual guns would make sound level predictions complicated but not an order of magnitude larger.

### 4.2. *Bangs did cause C-starts*

All those fish observed swimming while the gun fired showed a C-start causing a skip to one side at all ranges observed, with the maximum range being 109 m and sound pressure level of 195 dB (rel to 1  $\mu$ Pa). Analysis frame by frame shows all the fish responding in the same TV frame (one frame takes 20 ms and the sound wave travels 30 m during one TV frame). The reaction appeared to interrupt temporarily whatever the fish were doing and within 1 or 2 s, the fish were continuing with their previous activity. Startle or escape reflexes involving fast start responses allow fish to avoid sudden actual or potential danger in their environment (Domenici and Blake, 1991). Kinematics and performance of fish during fast start manoeuvres have received a lot of attention (reviewed by Domenici and Blake, 1997) since they may determine the outcome of predator–prey interactions in terms of feeding success or survival. The first detailed kinematic description of fast start movement was made by Weihs (1973) who separated the fast start movements of trout, *Salmo trutta*, into three kinematic stages. Stage 1: The preparatory stage, in which the fish changes from a straight position, into an L-shape; Stage 2: The propulsive stroke, in which the tail is moved perpendicularly to the heading of the fish, ending up again in an L-shape with the tail

pointing in the opposite direction; Stage 3: A variable stage in which the fish settles down to either a normal propulsive rhythm or returns to a straight configuration, gliding usually in a direction at an acute angle to the original orientation. After Weihs (1973) and Webb (1976), most of the researchers used the synonymous term “C-start” instead of “L-shape”. However, L-shape or more recently, its synonymous C-starts, are not the only mode of fast start swimming. Webb (1976) described also an S-shape during some of the fast start responses of rainbow trout, *Oncorhynchus mykiss*. At present, two main types of fast starts are recognised, C- and S-starts, in which the fish is bent into a “C”- or “S”- shape at the end of the first contraction of the lateral muscle (Domenici and Blake, 1997). Domenici and Blake (1997) stated that the S-starts were used by predators when attacking prey, whereas, C-starts are mainly seen when a fish is startled by a predator or experimenter. Although nothing is known about the mechanisms controlling S-starts (Eaton and Hackett, 1984; Domenici and Blake, 1997), C-starts are usually mediated by the Mauthner cells and associated neural networks (Zottoli, 1977; Eaton et al., 1977, 1981; Nissanov and Eaton, 1989). The Mauthner cells are a pair of identifiable hindbrain neurones that participate in the escape response of fishes (Lee et al., 1993). Zottoli (1977) obtained extracellular recording from the Mauthner cells of goldfish free to swim in an aquarium except for a tether containing the recording lead. He found that the Mauthner cell action potential (Mauthner spike) was followed by a prominent electromyogram of the contralateral body musculature when the fish were observed to display fast start behaviour. Similar results to Zottoli’s (1977) were found by Eaton et al. (1977, 1981). Eaton et al. (1981) reported that the Mauthner cell fired only once and preceded the initial contraction (Stage 1) of the C-type fast start. They stimulated the fish by dropping a ball into the aquarium and they reported that the experimental animals usually turned away from the side on which the ball was dropped. The pathway and the performance of the fish during the Mauthner-initiated component, Stage 1, was found to be stereotypic from trial to trial, whereas, components of the Stage 2, which is not mediated by the Mauthner cells (Eaton and Hackett, 1984), were quite variable (Eaton et al., 1981).

The fish filmed responding to the bang of the G. guns show the initial C-start superimposed on whatever phase of the tail beat cycle coincides with the bang. The fish veers violently to one side due to the involuntary, out of phase, contralateral contraction of its whole lateral muscle, being Stage 1 of the Mauthner reflex and then resumes control with voluntary movements of Stage 2, bringing it back on course. There did not appear to be any directionality in the C-start bending relative to the gun position. The present G. gun experiments indicated that the C-start generated by the seismic bang was not followed by any consistent direction change unless the sound source was associated with a visual stimulus.

#### 4.3. *Why so few directional responses?*

The lack of directional response to the bangs raises some important points of difference between our experiments and many others. In this study, the firing of the G. gun was presented without any other associated sounds. The gun was not moving so that any sequence of bangs showed no change in intensity when heard say by a fish positioned within the area of the study. The sound of the firing of the guns of a survey ship towing an array will be associated with the continuous ship noise, as well as showing a changing sound pressure level due to the approaching or receding intensity of both ship and bangs. These added features may well add information that is necessary

for the fish to respond with directed movements that might, for example, allow it to react and swim away, improving its comfort level, etc. This also suggests that the bang on its own is either too complicated or variable in its composition or too short to give directional information to the fish.

The fish population studied at Fish Rock is a resident population where the reef is part of their familiar home territory and it was possible that even if they could react directionally to the bangs they were not sufficiently irritated by them to elect to move elsewhere. Fish in different situations, for example, nomadic or migrating fish, might respond much more freely to the stimuli presented by seismic surveys.

The two tagged pollack that remained within the tracking area when the guns arrived had continued to show repeated daily rhythms up to the arrival of the diesel vessel deploying the guns, and pollack D then stopped moving away from the reef during the rest of the study. Fish E was less disturbed by the arrival of the boat and continued with daily movements until 23 August, but it showed the only marked reaction to the gun firing when, on 22 August after the gun fired at a range of 10 m, the fish immediately moved to a range of 30 m. At 10 m this fish might have seen the silhouette of the bubbles, formed at the first firing, rising to the surface and so reacted to the combined sound and visual stimulus.

#### 4.4. Repeatability of sound in a shallow site

The wave of sound recorded at 16 m (see Fig. 5c) had a first peak reaching 18,900 Pa at 3.1 ms followed 6.1 ms later by an inverted peak at  $-13,400$  Pa so that peak to peak is 210 dB (rel to  $1 \mu\text{Pa}$ ) or about 32,000 Pa. A third low-amplitude peak follows 4.2 ms later. The first peak to peak represents an 82 Hz wave, the second peak to peak 128 Hz and peaks 1–3 just 100 Hz. The lethal pressure change of 275,000 Pa or 229 dB (rel to  $1 \mu\text{Pa}$ ) in less than 1 ms (Larson, 1985) is never present. However, the detail within the slopes of the wave show that they are not simple sine waves and do contain samples of slopes representing quite different frequencies (see Fig. 5b). The components of the wave recorded at any point are the result of a complex combination of the pressure changes that have taken quite different paths. The waveform becomes more complex with distance from the source (see Fig. 4). Fig. 5 shows an example of the sound wave recorded at 16 m from the source where the first positive wave arrives directly from the gun through the water and is joined by a negative going wave of similar intensity which was delayed and inverted by reflection from the sea surface. As seen in Fig. 4, recordings made progressively further from the source show more and more added waves and complications of this sort. Fig. 3 shows that the amplitude of the gun pressure peaks are roughly predictable by spherical spreading theory and not by cylindrical theory. However, it is clear from our measurements that every position in our study area may receive a slightly different form of pressure wave and critical studies investigating the effects of guns should make direct measurements at the point of any observations or tests.

The negative pressure involved in the surface reflection wave (the negative peak in Figs. 5a and c) has been considered more damaging to fish within short range of the surface (discussed by Hubbs and Rechnitzer, 1952). One section of video tape (event F7, Table 2) shows 30–40 cm saithe swimming towards the gun at 16 m range and about 4 m from the sea bed and 10 m from the surface. When the gun fires they show the typical C-start, veer off course and then continue swimming in the direction of the gun (Fig. 12).

Damage to sensitive hearing organs such as the otolith haircell bed, semicircular canals or swimbladder might be expected at these high intensities and revealed by signs of disorientation. Those fish swimming rapidly away from the rising sand cloud towards the camera (event F8, Table 2) had encountered the firing of the gun at less than 5 m range and showed no disorientation or any evidence of losing their balance or righting reflex or buoyancy.

Despite the obvious and immediate C-start reaction seen in every fish for every bang of the gun, continuous observation of fish in the vicinity of the reef using time-lapse TV and tagged individuals did not reveal any sign of disorientation and fish continued to behave normally in similar quite large numbers, before, during and after the gun firing sessions.

#### 4.5. Two areas for future research

As mentioned in the introduction, a number of experiments concluded as here, that fish remain close to, and in the region of, the survey guns, apparently unconcerned and continuing their daily routines. These are mainly inshore and reef species, closely associated with a home territory and not easily moved. Future experiments might focus on the more long-term effects of repeated exposure to airgun bangs on details of their health and fitness. In contrast, other open-sea experiments have found indications of large-scale influences resulting in apparent movements of commercial fish species, for example, making them more or less accessible to fisheries. The nomadic fish like cod and haddock, and pelagic migrating species like mackerel and herring, are known to move long distances through feeding grounds to breeding grounds and so on. There is room here for skilful application of modern fish observation technology to investigate whether man is able to influence the detail of these large-scale fish movements by stimuli such as seismic surveys.

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