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Effects of Seismic Energy on Fish: A Literature Review

Effets de l'énergie sismique sur les poissons – Examen de la littérature

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ABSTRACT

The potential impacts of geophysical (seismic) surveys on adult and juvenile fish in Canadian waters are investigated through a literature review of laboratory and in situ studies on the behavioural, physical and biochemical responses of fish to sound, focusing primarily on impacts of airgun sources. Based on the limited number of studies that have been conducted to date, there is considered to be a high probability that some fish within the general vicinity (i.e. hundreds of meters) of a seismic survey operation will exhibit startle responses, changes in swimming speed or direction, and changes in vertical distribution, with recovery likely within minutes to hours after exposure. There is a lower but still reasonable probability that seismic surveys will influence the horizontal distribution and catchability of some fish under certain conditions, such as during migration of pelagic fish. If horizontal dispersion does occur, impacts are more likely to be observed over greater distances (kilometers) and for a longer duration (days). Seismic surveys are considered unlikely to result in immediate mortality of fish; however, sublethal physical damage and physiological impairments may occur within close proximity to an airgun source and could potentially result in delayed mortality or chronic effects. However, additional research is required to assess the intensity of sound levels or typical ranges from a known seismic source required to produce these types of effects. The potential for seismic surveys to disrupt communication and other sound-dependant activities of fish is essentially unknown, as is the long-term ecological significance of the impacts described above.

RÉSUMÉ

Les impacts potentiels des levés géophysiques (sismiques) sur les poissons, adultes et juvéniles, dans les eaux canadiennes sont étudiés dans le cadre d'un examen de la littérature. Les études examinées, réalisées en laboratoire et sur le terrain, concernaient les réactions comportementales, physiques et biochimiques des poissons au bruit et étaient concentrées principalement sur les impacts des détonations de canons à air. D'après le nombre limité d'études réalisées jusqu'à présent, on juge qu'il existe une probabilité élevée que certains poissons situés dans les environs (c. à d. quelques centaines de mètres) d'une zone où des activités de levé sismique se déroulent affichent des réactions de surprise et modifient leur vitesse de nage ou leur direction ou, encore, leur répartition verticale, avec un retour probable à la normale dans les minutes ou les heures suivant l'exposition. Il existe une probabilité moindre mais tout de même raisonnable que les levés sismiques influent sur la répartition horizontale et la capturabilité de certains poissons dans certaines conditions (p. ex. pendant la migration de poissons pélagiques). En cas de dispersion horizontale, les impacts sont davantage susceptibles d'être observés sur de plus grandes distances (kilomètres) et une plus longue période (jours). Les levés sismiques sont considérés comme peu susceptibles d'entraîner une mortalité immédiate des poissons; toutefois, des dommages physiques sublétaux et des problèmes physiologiques peuvent apparaître à proximité immédiate des canons à air et pourraient éventuellement causer une mortalité différée ou des effets chroniques. Il faut donc réaliser des recherches additionnelles afin d'évaluer l'intensité des niveaux sonores ou la portée type d'une source de bruit sismique connue qui entraînera l'apparition de ces types d'effets. Le potentiel de perturbation que représentent les levés sismiques pour les communications et d'autres activités fondées sur le son chez les poissons est en grande partie méconnu, et il en est de même pour l'importance écologique à long terme des impacts décrits ci-devant.

1.0 INTRODUCTION

This paper summarises literature that may be useful in determining the effects of airgun impulses on adult and juvenile fish. It includes a summary of what is known about the auditory sensitivity and use of sound by fish, and it presents the results of international studies on the behavioural, physical and biochemical reactions of a variety of fish species upon exposure to low-frequency (primarily airgun) sound sources.

2.0 USE OF SOUND BY FISH

An understanding of sound reception is vital to understanding the effects of noise, including seismic airgun noise, on any species. Thorough reviews of hearing and communication in fish can be found in Platt and Popper (1981), Hawkins (1981; 1986), and Popper et al. (2002). However, a brief summary of the structure and function of acoustic reception in fish is included here.

2.1 Sound Reception

Fish do not have external ears to help collect and direct sound waves towards internal hearing organs. Rather, sound waves pass through a fish's body until they reach the inner ear, which is composed of the utricle, the saccule, the lagena and three semicircular canals. The utricle, saccule and lagena (together referred to as the labyrinth) are membranous organs containing bony otoliths that vibrate in response to pressure waves. Vibration stimulates the surrounding hair cells, and this results in transmission of signals to the brain which are interpreted as sound. The semicircular canals present in the inner ear provide a fish with its sense of balance. They are fluid-filled with sensory hairs to detect rotational acceleration of the fluid.

Different fish species exhibit some minor differences in the basic structure of the inner ear, including but not limited to the shape of the semicircular canals, the size and shape of the otoliths, the structure of the saccules, the amount of sensory epithelium, and the orientation of hair cells. There is less variation in the lagena and the utricle, except for Clupeiforms (herrings and relatives) and several marine catfish in which the utricle is highly modified. This modification is thought to enhance detection at higher frequencies (Mann et al., 1998).

An alternate pathway for sound waves to reach the inner ear is via the swimbladder. Many fish species have a swim bladder, which is a gas-filled chamber (fat filled in some deep water species) that may also resonate in response to sound waves. The swimbladder acts as a pressure-to-displacement converter, where pressure waves are converted to vibrations that travel through tissue to the inner ear. In some fish (e.g., Cypriniforms), the swim bladder is connected directly to the inner ear through a series of small bones called Weberian ossicles (Hastings, 2002). This connection between swim bladder and inner ear has been shown to impart greater hearing sensitivity. Other types of modifications to the swimbladder that help to increase its connection to the inner ear include the suprabranchial chambers of labyrinth fish (Yan, 1998) and the tympanic bladders of mormyrids (Fletcher and Crawford, 2001). It has been hypothesized that swimbladder size and corresponding resonance frequency may have an influence on hearing sensitivity.

Fish posses another avenue for low-frequency sound reception called the lateral line, which consists of receptors called neuromasts (hair cell clusters) that are specialised for the detection of water movement relative to the fish. The lateral line acts as a near-field acoustic receptor in a cross between hearing and touch. It may function in a variety of behavioural contexts, including prey localization, predator avoidance, communication during spawning, and navigation around obstacles (Webb, 2001). The relationship between the lateral line and the auditory system of fish is not fully understood and continues to be investigated (Webb, 2002; Weeg and Bass, 2002).

2.2 Acoustic Sensitivity

The acoustic sensitivity of a fish is usually expressed by its sound detection and discrimination thresholds, i.e., the range of frequencies perceived and intensities required to perceive them, and is typically presented in the form of an audiogram (Fay, 2002). Many of these thresholds have been investigated using conditioning methods, in which fish are trained to response to a stimulus. More recently, electrophysiological methods have been used to measure direct physiological responses of hearing receptors to stimulus, e.g., auditory brainstem response technique.

Audiograms have been produced for a variety of fish species. Comparison of these audiograms demonstrates variability in the acoustic sensitivity of fish that is not only associated with species differences but also reflects differences in methodology, differences between individuals and even within individuals. For example, the threshold for a fish measured in a quiet environment is not fixed but may vary with age and physiological state (Hawkins, 1981). There are numerous species for which audiograms have not been developed.

Frequencies detected by fish generally range from 50 to 3000 Hz, though some species are able to detect much higher frequencies. For example, the American shad (*Alosa sapidissima*) is able to detect ultrasonic frequencies up to 180 kHz (Mann et al., 1997). Seismic airguns in water generate sound waves with dominant frequencies in the range of 20-150 Hz, thus would typically be detectable to most fish species. Higher frequencies are also generated during operation of seismic airguns, though at lower intensity.

Duty cycle, i.e., the ratio of time during which sound is produced to the time during which no sound is produced, also influences the acoustic sensitivity of fish to a sound source. In general, it is expected that fish will be less sensitive to intermittent sounds than to continuous sounds at the same intensity.

Sensitivity to sound intensity varies between species. For example, Chapman and Hawkins (1973) determined the hearing threshold of Atlantic cod (*Gadus morhua*) in open water to be ~80 dB re 1 μPa, where the hearing threshold of Atlantic salmon (*Salmo salar*) was determined to be ~99 dB re 1 μPa at a frequency of 160 Hz (Hawkins and Johnstone, 1978). Research on intensity thresholds (lowest levels detected) has been much more extensive than research on intensities required to cause harm. Exposure to intense sound can cause hair cells to die, which may result in loss of hearing. The capacity to regenerate hair cells and regain hearing exists in some species (Corwin and Cotanche, 1988), but only a limited number of species have been studied. Research on the effects of airgun impulses on fish is expected to contribute to a better understanding of the effects of low frequency, high-intensity sound on fish in general.

2.3 Use of Sound by Fish

Fish are known to produce sounds using five general mechanisms (Kaatz, 2001):

1. swimbladder pulsations
2. stridulation
3. hydrodynamic movement
4. body and tendon vibration, and
5. air release.

The reasons for sound production are less certain but may be related to reproduction (e.g., courtship, mate selection, parental care), aggression (e.g., territory defence) and possibly as an escape response (e.g., some fish produce intense sound when captured). Sound interception also plays an important role in fish ecology. For example, many species are attracted to the sounds of their prey while others react to sounds made by their predators or rivals (Myrberg, 2002).

In 1970, a book was published by Fish and Mowbray entitled “Sounds of Western North Atlantic Fishes.” They examined 218 species from 59 families and found biological sounds from 153 species in 36 families. Forty-seven of these species were observed generating spontaneous sounds (i.e., without stimulation). More detailed investigations of sound production have been conducted for a variety of species worldwide. Of particular interest in the Canadian context may be the two studies on Atlantic cod and haddock (*Melanogrammus aeglefinus*) that are described below. Note: the scientific and common names of all fish species discussed in this report are provided in Appendix A.

Sounds produced by cod include deep "grunts" made by swim bladder contractions (duration = 60 to 200 ms, source level = 120-133 dB re 1μPa @ 1m, frequencies = 50 to 120 Hz), short "knocks" probably made by a single contraction of the sonic muscle, and long series of knocks (longest recorded lasted for 37 sec and consisted of 181 individual knocks). Grunts and knocks were associated with different patterns of behaviour such as aggression, chasing and escaping. Series of knocks (not recorded in captivity) seem to be associated with territorial behaviour or examination of the seabed (Midling et al., 2002).

Male haddock produce a wide range of sounds associated with mating behaviour. "Solitary display" was always accompanied by a train of regularly spaced knocks (interval between knocks = 60 to 140 ms). As courtship proceeds, the male moves around the female in tight circles and emits humming sounds, modulated in amplitude and repetition rate. Females alone in a tank produced short slow sequences of knocks (Casaretto and Hawkins, 2002).

The potential for seismic noise to disrupt communication (sound production, reception and interception) in fish is essentially unknown. Mechanisms for disruption of communication could include masking, behavioural responses (e.g., cessation of sound production) and hearing damage.

Recent research has identified another potential use of sound by fish. A study by Simpson et al. (2004; 2005) has demonstrated that settlement of fish larvae on reefs can be enhanced through use of sound cues (i.e., more settlement occurred on noisy reefs than on quiet reefs), this and studies reported in Tolimieri et al. (2000; 2002) suggest that fish larvae may use reef sounds to guide settlement behaviour.

3.0 EFFECTS OF LOW FREQUENCY SOUND ON FISH

3.1 Methodology

A total of twenty-three experimental and opportunistic studies on the effects of airgun impulses on fish conducted world-wide between 1969-2005 were reviewed and are summarized for reference purposes in Appendix B. Results are further summarized by effect type in Section 3.2. Efforts have been made to enable comparison of experimental results by providing sound source levels, distance to the source, and received sound pressure levels associated with each result. Of particular use for comparison are the received sound levels linked to a particular impact. Where received sound levels have not been provided in the literature, efforts have been made to estimate these levels based on the known or suspected source levels and a calculation of the transmission loss due to spherical (20logR) or cylindrical (10logR) spreading, where R is the distance between the source and the receptor. These calculations are meant to provide only a very course estimate of received levels.

Since the use of airgun arrays is the primary method of seismic exploration in Canada, the focus of this review is on the impact of airgun impulses. However, the limited number of studies using airguns as the sound source made it prudent to also consider studies on the effects of other types of low frequency sounds. Experimental studies on the effects of low-frequency sound on marine and freshwater fish using non-airgun sources are presented in Appendix C and are summarized by effect type in Section 3.3.

Numerous literature reviews of seismic impacts have been published previously. Supplemental information provided by these reports has been included in Appendix D. For example, references to studies that were unavailable to the current reviewer and therefore not summarized in Appendices B or C are included in Appendix D. Results of these studies are included in Sections 3.2 and 3.3 where appropriate; however, given the potential for misreporting of second-hand information, these results are given only secondary consideration in the development of conclusions.

It is recognized that research on the effects of seismic noise on fish is in its infancy and many knowledge gaps remain. Conclusions of this report are based upon the information available at the time of the review and they should be re-evaluated as new information becomes available.

3.2 Results of Experimental Studies using Airgun Sources

Experimental and opportunistic studies conducted world-wide from 1969 to 2005 on the effects of airgun impulses on fish are summarized in Table 1. Sound pressure levels are reported in dB re 1 µPa; however, whether these represent zero to peak (o-p), peak to peak (p-p), or root mean square (rms) measures was not always evident from the literature. Appendix B contains additional detail on each experiment, including objectives, methodology, results and conclusions.

Table 1. Impacts of Noise Generated by Seismic Airguns on Fish.

Effect Type	Source levels (dB@1m)	Meters from source	Received levels (dB)	Results	Reference
Physical Effects					
Mortality	226[1]	2	220[2]	Some cod and plaice died within 48 hrs; internal injuries reported. No controls to test for significance.	Matishov (1992)
	20 cui (2000 psi)	1	234	One salmon died (n=10) 60 hours after exposure; however, no external aberrations or internal hemorrhaging were observed. Subsequent reports make no mention of this fatality.	Weinhold and Weaver (1972)
Physical damage	230[1]	0.6-1.5	226-234[2]	Swim bladder damage in 2 arctic cisco (n=14).	Falk and Lawrence (1973)
		~3	234 (p-p)	Swim bladders damaged in 73% of exposed adult anchovy as compared to 11% of controls (p=0.01).	Holliday et al. (1987)
	220-240[1]	0.5	226-246[2]	Half of exposed fish suffered damage to blood cells or internal bleeding. Eye injuries also reported.	Koshleva (1992)
	226[1]	4	214[2]	Blindness in cod and plaice. No controls used.	Matishov (1992)
	222.6 (p-p)	5-800	< 212	Significant damage to sensory epithelia (ablated ear cells) in pink snapper examined 58 days after exposure. No mortality.	McCauley et al. (2003)
	20 cui (2000 psi)	10	208	Dislocated tissue within swimbladder of one salmon (n=10). This result is not mentioned subsequently and may have been discarded as unrelated to airgun exposure.	Weinhold and Weaver (1972)
	240 cui (2000 psi)	1	241	Damaged operculum in one salmon (n=10). This was considered to be unrelated to exposure as missing tissue did not appear to be of recent removal.	

Hearing loss	202	13, 17	205-210	Statistically significant hearing loss immediately upon exposure of adult northern pike to 5 pulses at 400 Hz and exposure of lake chub to 5 and 20 pulses at 200, 400 and 1600 Hz. Recovery within 18 hrs.	Popper et al. (2005)
No hearing loss	202	13, 17	205-210	No hearing differences between exposed and control broad whitefish or juvenile northern pike.	
No physical damage	256 (o-p)	180	210[3]	No physical damage observed in European sea bass.	Santulli et al. (1999)
	230[1]	3.0-3.4	219-220[2]	Stress observed in 2-15 arctic cisco but no overt signs of physical damage.	Falk and Lawrence (1973)
	230 (o-p)	2	224	Some freshwater fish temporarily stunned, but recovery within 0.5 hrs; no mortalities; no damage to hearing or internal structures; no histopathology abnormalities attributed to airgun exposure. Some abnormalities attributed to preservation.	IMG (2002)
		~3	215-222 (p-p)	Healthy ("groomed") anchovy exhibited no swimbladder damage at these levels. Results are not considered statistically significant.	Holliday et al. (1987)
	229	150-4000	142-186 (p-p)	No mortalities of rainbow trout or Atlantic salmon observed.	Bjarti (2002)
	256	> 54	< 221[2]	No sandeel mortality attributable to airgun exposure. Where mortalities occurred, they were attributed to handling procedures (i.e., similar in control and experimental fish).	Hassel (2003)
	222, 231	1-10	202-231[2]	No mortality of cod fry observed.	Dalen and Knutsen (1987)
	202	13, 17	205-210	No mortality of fish held for 24 hours after exposure. No obvious morphological damage to swimbladder, eyes, gills or other organs.	Popper et al. (2005)
	220-240[1]	1	220-240[2]	No acute effects observed at this distance.	Koshleva (1992)
Physiological Effects					
Change in physio-logical measures	256 (o-p)	180-6500	194-210[3]	Increase in sea bass serum cortisol, glucose and lactate immediately after exposure with recovery in 72 hrs. Decrease in serum adenylates. Muscle and liver cortisol increased initially but returned to normal in 72 hrs. Glucose and lactate levels in liver increased over 6 hrs. Glucose and lactate levels in muscle increased from 6-72 hrs. cAMP in muscle and liver increased over 72 hours with no return to pre-exposure levels.	Santulli et al. (1999)

No effect		200-9800	146-195 (rms)	No statistically significant stress increases which could be directly attributed to airgun exposure.	McCauley et al. (2000)
Behavioural Effects					
Startle response	256 (o-p)	180-2500	199-210[3]	Startle response from European sea bass starting when vessel approached within 2500 m, return to pre-exposure behaviour when vessel passed to 1 nm.	Santulli et al. (1999)
	223 (o-p)		200-205	Startle response by black and olive rockfish.	Pearson et al. (1992)
		5.3-195	195-218	Startle (c-start) reaction of pollock to all airgun shots.	Wardle et al. (2001)
	256	> 54	< 221[2]	Startle response observed in some sandeel. No direct relationship between response and distance to vessel within 10 x 10 km survey area.	Hassel et al. (2003)
	229	150-4000	148-186 (p-p)	On 8 of 124 seismic shots, some startle response was observed. Minimum level of observed reaction for trout was 148 dB while minimum level of observed reaction for salmon was 167 dB. Trout fed normally after exposure.	Bjarti (2002)
			182-195 (rms)	Persistent startle (c-start) response in all trials. Greater response in small fish.	McCauley et al. (2000)
Change in vertical position	220[1]	< 55	~185[2] at 55 m	Downward movement of whiting to form compact layer at 55 m.	Chapman and Hawkins (1969)
	223 (o-p)	~82-183	186-191	Decrease in average rockfish aggregation height.	Skalski et al. (1992)
	249.9	100-300	200-210	Statistically significant reduction in echo sounder abundance of demersal fish (36% reduction); fish presumably forced to bottom since catch rates increased by 34 and 290%.	Dalen and Knutsen (1987)
	222.6	20, 50	197, 189[2]	Blue whiting and mesopelagics descended in water column (20 and 50 m deeper respectively).	Slotte et al. (2004)
	256	> 54	< 221[2]	Sandeel tended to remain higher in enclosure.	Hassel et al. (2003)
	223 (o-p)		177-180	Black rockfish schools collapsed to bottom when airgun started. Returned to pre-exposure behaviour within 20-60 min.	Pearson et al. (1992)
	223 (o-p)		186-199	Vermillion and olive rockfish either rose in water column and eddied at increased speed or moved closer to bottom and became almost motionless. Returned to pre-exposure behaviour within 20-60 min.	

			>156-161 (rms)	Aggregation in bottom centre of enclosure.	McCauley et al. (2000)
	256 (o-p)			Change in vertical distribution of pelagic fish. In particular, reduced acoustic density within the top 16 m.	La Bella et al. (1996)
Change in horizontal distribution	249	< 37 km		Acoustic density of cod and haddock reduced by 45% during exposure, continued decrease to 64% 5 days after exposure. (250-280 m water depth)	Engas et al. (1996)
	223	< 37 km		Average density of mesopelagic fish (including herring and blue whiting) was lower in seismic survey area, with increasing abundance at distance. Fish density seemed higher about 37 km from center of survey area.	Slotte et al. (2004)
	249.9	100-300	200-210	Statistically non-significant reduction in echo sounder abundance of blue whiting (54% reduction) and small pelagics (13% reduction). Presumed to have migrated out of area (100-300 m water depth).	Dalen and Knutsen (1987)
Change in swimming behaviour			156-161 (rms)	Faster swimming and formation of tight groups.	McCauley et al. (2000)
	256	180	210[3]	Sea bass bunched in the center of the enclosure with random orientation and increased swimming speed. Recovery within 1 hr of exposure.	Santulli et al. (1996)
	256	> 54	< 221[2]	Slight increase in tail beat frequency as vessel approached.	Hassel et al. (2003)
	222, 231	1-10	202-231	Temporary problems with balance in cod fry. Recovery after a few minutes. No significant difference in feeding behaviour as compared to controls (202-222 dB).	Dalen and Knutsen (1987)
	223 (o-p)		177-180	Increasingly tighter schools of blue rockfish with increasing sound levels.	Pearson et al. (1992)
			< 218	Day-to-night movements of two tagged pollock altered during longer-term exposure to airguns.	Wardle et al. (2001)
No behavioural effect	250[1]			Most tagged sea bass were recaptured within 10 km of release site (5-30 m water depth).	Pickett et al. (1994)
			< 218	Two tagged pollock did not move away from reef (10-20 m water depth).	Wardle et al. (2001)
	256			Non-enclosed sandeel observed in survey area (54-56 m water depth).	Hassel et al. (2003)
	202	13, 17	205-210	Normal swimming behaviour of northern pike, broad whitefish and lake chub during exposure.	Popper et al. (2005)
	230 (o-p)			No observed “herding” of freshwater fish in front of seismic vessel during operation (river environment).	IMG (2002)

Fisheries Effects					
Change in catch or effort	249.9	100-300m	> 200 at depth[2]	Increase in demersal fish catch by 34% and 290%.	Dalen and Knutsen (1987)
	239	< 9.3 km	161[1] at 5 km	Reductions of 55-80% in longline catches of cod within 9.3 km (5 nm) of seismic survey area.	Løkkeborg (1991)
	239-250	< 9.3 km	160-171[1]	Reductions in shrimp trawl by-catch of cod by 79 and 83% within 9.3 km (5 nm) of seismic survey area. Increases of cod by-catch in saithe trawl of 300%. Return to pre-exposure catches within 12-24 hrs.	Løkkeborg and Soldal (1993)
	223 (o-p)	< 165 m	186-191	Average decline in rockfish catch-per-unit effort of 53% within seismic survey area.	Skalski et al. (1992)
	249	< 33 km		Statistically significant reductions in trawl and longline catch of cod and haddock within a 74 km^2 study area upon exposure to a seismic source. Trawl catch of cod reduced by 69% within the 5.6x18.5 km seismic survey area and 45-50% outside seismic survey area. Trawl catch of haddock reduced by 68% within seismic survey area, 56% 2-17 km from survey area and 71% 30-33 km from survey area. Longline catch reduced by 45% in survey area, 16% at 1.9-5.6 km from survey, 25% at 13-17 km from survey. Longline catches of cod tended to increase within the seismic survey area, while haddock longline catches were reduced by 67% within the seismic survey area.	Engas et al. (1996)
No effect on fisheries	250[1]	1-23 km		No significant change in hook and line catch rate of European sea bass.	Pickett et al. (1994)
	256 (o-p)			No significant changes in trawl or gillnet catch.	La Bella et al. (1996)
	229	< 7 km		No change in catch rates directly attributable to seismic operations.	Bjarti (2002)
	256	< 55 km		No change in catch rates directly attributable to seismic operations.	Hassel et al. (2003)
				Statistical analysis of logbooks showed no statistically significant effect of seismic surveying on catch rates; however, 75% of fishermen believed they had observed an effect. No lasting impacts on fisheries success.	Jakupstovu et al. (2001) reported in Gausland (2003)

[1] source levels as estimated by Turnpenny and Nedwell (1994).
[2] received levels as estimated by spherical spreading (20logR).
[3] received levels as estimated using spherical spreading, 20logR, to water depth and cylindrical spreading, 10logR, for remaining distance.

3.3 Results of Experimental Studies using Low Frequency, Non-Airgun Sources

Experimental studies on the effects of low-frequency sound on marine and freshwater fish using non-airgun sources are summarized by effect type in Table 2. Additional experimental details can be found in Appendix C.

Table 2. Impacts of Low Frequency (Non-Airgun Source) Noise on Fish.

Effect Type	Source Type	Frequency (Hz)	Duration	Received levels (dB)[1]	Results	Reference
Physical Effects						
Mortality	Watergun (8610 cui, 229 dB at 1m)			223[2] at 2m	90% mortality of cod fry observed, with evidence of ruptured swimbladders and hemorrhaging.	Dalen and Knutsen (1987)
				213[2] at 6m	1 cod fry died after 2 days.	
	Pure tones (DC = 100%)[3]	150, 400	0.5-2 hrs	204	25% mortality of goldfish due to internal haemorrhaging.	Hastings (1990) reported in Turnpenny et al. (1994)
				192-198	50-56% mortality of gouramis (Belontiidae) due to internal haemorrhaging.	
	Electromagnetic transducer	95, 410		> 170	Significant mortalities of brown trout 24 hrs after exposure, with swimbladder and eye damage.	Turnpenny et al. (1994)
		95		130-160	47% mortality of whiting after 24 hours.	
Physical damage	Pure tones (DC = 100%)	50-400	hours	180	Damage to inner ear structure (ciliary bundles) of cod.	Hastings (1990) reported in Turnpenny and Nedwell (1994)
		250, 500	2 hrs	197, 204	Damage to inner ear structure (ciliary bundles within saccule and lagena) of goldfish.	Cox et al. (1986) reported in Hastings et al. (1996)
	Sound projector (DC = 100%)	300	1 hr	180	Damage to small regions of the striola of the utricle and lagena in 4 of 5 oscar. Damage developed over a period of 1-4 days.	Hastings et al. (1996)
	Loudspeaker	50-400	1-5 hrs	180	Loss of ciliary bundles on sensory cells of saccule in Atlantic cod.	Enger (1981)
	Electric percussion caps	500-5000	10 impulses	246 at 1.3m	Damage to vascular endothelium with recovery after 12 hours. Impacts to physiological function. No mortalities observed after 7 days.	Sverdrop et al. (1994)
	Electro magnetic transducer	410		< 180	Small number of bass suffered from swimbladder damage at this frequency.	Turnpenny et al. (1994)
		200		130-160	Small number of whiting exhibited ruptured swimbladders.	

Hearing loss	White Noise	100-10000	10 min - 24 hrs	160-170	Temporary shift in goldfish hearing (5 dB) after only 10 min exposure; Significant threshold shift (28 dB) after 24 hours.	Smith et al. (2004a)
		600-4000	24 hrs	130	Temporary threshold shift in goldfish ($p<0.05$).	Smith et al. (2004b)
		100-10000	24 hrs	140, 160, 170	Temporary threshold shift in goldfish ($p<0.05$).	
		800	28 days	164-170	Slight threshold shift in hearing of tilapia ($p=0.02$)	
	Audio generator (pure tones)	300, 500, 800 & 1000	4 hrs	149 (also 146 dB at 500 Hz)	Statistically significant threshold shift was obtained for goldfish at these levels.	Popper and Clarke (1976)
	White Noise	1000-2000	1 hr	142	Statistically significant threshold shift in fathead minnow. After 2 hrs exposure at 1500 and 2000 Hz, recovery was observed within 6 days. After 24 hrs exposure to 800 and 1000 Hz, recovery was observed within 1 day; no recovery was observed within 14 days at 1500, 2000 Hz.	Scholik and Yan (2001)
		800-2000	2 hrs			
		300 - 2000	24 hrs			
No hearing loss	White noise	300 - 2000	2-24 hrs	142	Slight, non-statistically significant threshold shift in bluegill sunfish (hearing generalist).	Scholik and Yan (2002)
		100-10000	7 days	164-170	No significant shift in auditory threshold of tilapia.	Smith et al. (2004b)
No physical damage	Pure tones	100-2000	hours	150	No damage to goldfish	Hastings (1990) reported in Turnpenny and Nedwell (1994)
	Sound projector (DC = 100%)	60	1 hr	100, 140, 160	No damage to inner ear cells attributable to sound exposure.	Hastings et al. (1996)
		300		100, 140		
	(DC = 20%)			100, 140, 160		
	Electro magnetic transducer	410, 790, 1580	24 hrs	130-180	No mortalities of European sea bass.	Turnpenny et al. (1994)
				155-177	No signs of injury to sole.	
				160	No significant mortalities of brown trout.	
				130-160	No significant mortalities of whiting.	

Physiological Effects						
Change in physio-logical measures	White Noise	100-10000	10 min	160-170	Noise exposure significantly increased blood cortisol levels (p=0.01) as compared to controls.	Smith et al. (2004a)
	Electric percussion caps	500-5000	10 impulses	246 at 1.3m	Blood cortisol levels decreased 6-12 hrs after exposure, with returns to pre-exposure levels within 24 hrs. Plasma adrenaline peaked after 6 hrs, was significantly elevated at 12 hrs but not after 24 hrs. Noradrenaline declined significantly over the 48 hr post-exposure period. Atrial levels of adrenaline declined after 24-48 hrs. No significant changes in plasma chloride.	Sverdrop et al. (1994)
No effect	White Noise	100-10000	1 hour to 21 days	160-170	Noise exposure did not significantly alter blood cortisol or glucose levels as compared to controls.	Smith et al. (2004a)
Behavioural Effects						
Stunning	Pure tones	150, 400		192-198	Transient stunning of fish. Recovery typically within 30 min.	Hastings (1990) reported in Turnpenny and Nedwell (1994)
	Electric percussion caps	500-5000	10 impulses	246 at 1.3m	Cessation of movement in Atlantic salmon for a few minutes.	Sverdrop et al. (1994)
Loss of equilibrium	Pure tones	250-500	~2 hrs	182-204	Fatigue and loss of equilibrium in goldfish.	Cox et al. (1986)
	Watergun (8610 cui, 229 dB at 1m)			213 at 6m	Balance problems observed but most recovered.	Dalen and Knutsen (1987)
Avoidance response	Pneumatic popper	20-1000	2 hrs	176	Alewife effectively excluded from passing through an opening 9 m wide.	Haymes and Patrick (1986)
	Pure tones (DC = 100%)	100-500, ramped at 4.5		108-138	Alarm response and avoidance reaction of bass and Atlantic salmon.	Turnpenny et al. (1993) referenced in Turnpenny and Nedwell (1994)
		100-500 ramped at 4.5		138	Avoidance reaction of adult twaite shad. No mortalities.	Turnpenny et al. (unpub) reported in Turnpenny and Nedwell (1994)
	Electro magnetic transducer	95		128	Behavioural avoidance threshold for bass.	Turnpenny et al. (1994)

	Amplified electronic signal (DC=50-77%)	200-1000		102-111	Avoidance reaction of adult Pacific herring.	Swartz and Greer (1981) reported in Turnpenny and Nedwell (1994)
	Pure tones (DC = 100%)	100-500 ramped at 4.5		138	Reduction of European sea bass catch at power station intake by 39%.	Thatcher and Irving (1992) reported in Turnpenny and Nedwell (1994)
Startle reaction	White Noise	100-10000		160-170	Initial startle response in goldfish at onset of noise exposure that lessened within minutes.	Smith et al. (2004a, 2004b)
	Electromagnetic vibrator (single pulses)	80, 92		137-142	Startle reaction of juvenile herring. No mortalities.	Blaxter et al. (1981) reported in Turnpenny and Nedwell (1994)
	Electro magnetic transducer	410, 790		150	Startle reaction in bass observed at start-up. No habituation observed.	Turnpenny et al. (1994)
		95, 200, 410			Slight reaction observed in whiting, but not sustained over time. Not considered significant.	
No response	Pure tones (DC=100%)	100-500, ramped at 4.5		138	Virtually no effect on eels. Eels touching source were startled when it was turned on.	Turnpenny et al. (1993) reported in Turnpenny and Nedwell (1994)
	White Noise	100-10000	7-28 days	161-170	Tilapia did not exhibit a startle response to the sound levels tested. No avoidance behaviour.	Smith et al. (2004b)

[1] Sound pressure levels are reported in dB re 1 µPa.
[2] received levels as estimated by spherical spreading (20logR)
[3] DC (duty cycle) is described in Section 2.2.

3.4 Consideration of Other Literature Reviews

Literature reviews can offer an alternative perspective on the results of experimental studies. They can also be a useful source of supplemental information, such as estimations of source and received sound levels or experimental details that have not been previously reported. Corrections to preliminary reports have also been identified in literature reviews. For the purposes of this report, additional experimental details or corrections identified in literature reviews were only taken into account where the author of the literature review was involved in the original study. In general, literature reviews are more likely to summarize experimental studies than provide critical analysis of the methodologies employed. However, the study conducted by Engas et al. (1993; 1996) on large-scale (up to 33 km) dispersion of groundfish upon exposure to seismic survey activity in the North Sea and the study by McCauley et al. (2003) on damage to the inner ear of fish upon exposure to airgun impulses, have been informally critiqued by the petroleum industry. Concerns with the Engas et al. (1993; 1996) study were related to the analysis and display of experimental results. In particular, a non-peer reviewed report by Gausland (2003) claims that the graphs provided in the published literature do not show a clear trend of reduced catch rates that can be directly attributable to seismic noise. However, no statistical analysis to support this claim is provided. Concerns with the McCauley et al. (2003) study were related to sampling methodology, quality control and incomplete reporting of results (opinion expressed by the International Association of Oil and Gas Producers).

Previously conducted literature reviews contained references to four studies on the effects of airgun noise that were not summarized in Appendix B. These included one study of logbook data by Jákupstovu et al. (2001), which was not able to demonstrate statistical effects of a seismic survey on catch rates. Nonetheless, the author concluded that since 75% of fishermen who were interviewed felt that they had observed some effect, the possibility that effects had occurred should not be discounted. A study by Matousek et al. (1988) investigating the potential for noise to exclude fish from a power station intake found that a single airgun of source level 205 dB and bandwidth of 50-70 Hz caused avoidance reaction of alewife at 181 dB re 1 µPa. This is similar to results demonstrated by Haymes and Patrick (1986). A preliminary study by Greene (1985) on the effects of airgun noise on rockfish was also reported. Results of this study were inconclusive, but indicated reductions in catch rates and inconsistent behavioural responses. Subsequent studies by Pearson et al. (1992) and Skalski et al. (1992) explore these responses in more detail and are included in this review.

4.0 DISCUSSION

4.1 Direct Mortality

Studies conducted to date have not clearly demonstrated the potential for immediate mortality of adult fish, even at very close proximity to an airgun (within 2 m). While experimental fish died during experimentation in some studies, these mortalities were not significantly different from mortalities of control fish where controls were used and therefore were attributed to handling stress. At an international conference, Matishov (1992) reported that some cod and plaice had died within 48 hrs of exposure to an airgun. However, experimental details were not provided and it is not known whether controls were used. Weinhold and Weaver (1982) initially reported one Atlantic salmon fatality upon exposure to an airgun source, but no obvious signs of injury were observed and this death was not mentioned in subsequent publications. Fish mortalities may be more likely to occur upon close exposure to a watergun source (Dalen and Knutsen, 1987) or to high intensity (>200 dB re 1 μPa) pure tones over a period of hours. Based on studies conducted to date, it is considered unlikely that widespread, immediate adult fish mortality would result from seismic surveying using a typical airgun array.

4.2 Structural Damage

Six out of eight studies that examined adult fish specifically for sub-lethal physical effects following close exposure to airguns found some evidence of damage to one or more organs including damage to swim bladders, ablated ear cells, internal bleeding, or blindness. Most damage occurred upon exposure within 5 m of the source. The experiment by McCauley et al. (2003) on impacts of airgun noise to the inner hearing structures of pink salmon indicates damage to sensory epithelium (ablated hair cells) at peak to peak sound levels of 212 dB re 1 μPa. The exact levels/distance at which such damage may have occurred is unknown since the airgun was towed repeatedly from a maximum distance of 800 m to a minimum distance of 5 m. Damage may have occurred at any point during this exposure period, or as a result of the cumulative exposure. Weinhold and Weaver (1972) initially report hemorrhaging adjacent to kidneys, dislocation of tissue inside the swimbladder, and a missing part of a operculum then subsequently discounted these results as being unrelated to seismic exposure. Exposure to other sources of high-intensity, low frequency sound have also resulted in damage to the inner hearing structures of fish, though typically after repeated exposure (several hours) to sounds with relatively high duty cycles (50-100%). However, it is reasonable to conclude that physical damage, including damage to ear cells, may occur within close proximity to an airgun. The exposure/effect relationship and potential for recovery has not been clearly established for these types of effects. Additional research would be required to resolve this question.

4.3 Temporary or Permanent Hearing Loss

Very few, if any, studies on temporary or permanent hearing loss in fish have been conducted using an airgun source. However, a small number of studies have been conducted using other low frequency sound sources, the results of which may be useful in determining the potential for airgun impacts. Of particular interest are the frequencies and intensities required to generate shifts in the auditory threshold of fish, the likelihood and timing of recovery from such shifts, the differences in effect likely to be elicited in various fish species and the mechanisms by which these effects may occur. Of the five studies reviewed, four found evidence of temporary threshold shift after exposure to varying durations of white noise or pure tones. Frequencies causing effects ranged from 100 – 10,000 Hz at sound pressure levels of 130 – 170 dB re 1 μPa.

Small (5 dB) threshold shifts in goldfish, a hearing specialist, were observed after only 10 minutes of exposure, while much larger shifts (28 dB) were observed after 24 hours of exposure. Thus impacts on hearing may occur quickly and may increase with exposure duration. However, no significant increase in threshold shift was observed in goldfish upon exposure to an additional 2-20 days of noise, i.e., maximum hearing loss in goldfish occurred within the first 24 hours of exposure (Smith et al., 2004a). Sound pressure level and frequency also played a role in the extent of hearing loss in goldfish. For example, the threshold shift averaged across all frequencies tested was ~7 dB for a sound pressure level of 130 dB re 1 μPa but was ~32 dB for a sound pressure level of

170 dB re 1 μPa (Smith et al., 2004b). In this experiment, a linear relationship between sound pressure level and threshold shift was observed for each frequency tested, i.e., threshold shift increased linearly with increasing sound pressure level. Thresholds shift also varied significantly with frequency. For example, exposure to a sound pressure level of 149 dB re 1 μPa resulted in threshold shifts of 18-27 dB at 800 Hz but only 7-9 dB at 500 Hz (Popper and Clarke, 1976). While threshold shifts tended to occur at more sensitive hearing frequencies, this experiment obtained the greatest threshold shifts in goldfish at 800 Hz. Goldfish generally hear best at frequencies between 400-600 Hz.

The ability of fish to recover from noise-induced shifts in auditory threshold is of interest when determining the potential for long-term impacts. Threshold shifts in goldfish were found to be temporary in all studies reviewed. For example, goldfish exposed to four hours of pure tones (300-1000 Hz at 149 dB re 1 μPa) recovered their hearing within 24 hours (Popper and Clarke, 1976). Flathead minnow, another hearing specialist, recovered within a day after exposure to 24 hours of 142 dB re 1 μPa at 800 and 1000 Hz; however, flathead minnows exposed to the same sound pressure levels and duration but at 1500 and 2000 Hz did not recover even after two weeks (Scholik and Yan, 2001). It is possible that use of these frequencies may have resulted in inner ear damage and thus permanent threshold shift. It was suggested that further studies are required on the relationship between inner ear damage and changes in threshold shift.

Only slight temporary threshold shifts were observed in tilapia, a hearing generalist, even after exposure to 170 dB re 1 μPa at 800 Hz for 28 days (Smith et al., 2004b). Bluegill sunfish also demonstrated minimal loss of hearing upon exposure to white noise (Scholik and Yan, 2002). However, Hastings and Popper (2005) note that hearing generalists are more likely to be impacted by acoustic particle velocity than sound pressure level. The previously described experiments only investigated the impacts of sound pressure level and frequency on hearing loss.

4.4 Physiological Effects

Only two studies on the physiological effects of airgun exposure were available for this review. One study detected significant changes in cortisol, lactate, glucose, and adenylates of European sea bass exposed to an airgun source at a distance of 180-6500m as compared to controls (Santulli et al., 1999), which is characteristic of primary and secondary stress response. Most of these parameters returned to pre-exposure levels in the 72 hours following exposure (except cAMP). Upon exposure, many of these fish had exhibited startle and alarm responses. Received sound levels were not measured. Another study (McCauley et al., 2000) indicated no significant change in cortisol, glucose and white blood cell counts in fish that could be directly attributed to airgun exposure (146-195 dB rms).

Studies using other low frequencies sound sources contribute additional information on the physiological reaction of fish to noise. Exposure of Atlantic salmon to 10 impulses of 2 MPa (246 dB re 1 μPa, 500-5000Hz) within several meters resulted in damage to vascular endothelium and a suppressed stress response, with recovery over time (Sverdrop et al., 1994). The observed behavioural response of these fish was to freeze, rather than to exhibit an alarm response. As described below, exposure of fish to airgun impulses tends to result in startle (C-start) and alarm type responses rather than in immobilization. This suggests that cellular function remains intact and thus a physiological stress response may be possible. Goldfish exposed to white noise at 160-

170 dB re 1 μPa for 1 to 21 days did not exhibit a long-term stress response, i.e., no significant difference in blood cortisol or glucose concentrations as compared to controls over these durations. However, a statistically significant increase in blood plasma cortisol was observed after the first 10 minutes of exposure, which is the same timeframe during which temporary threshold shift occurred and startle response was observed. Cortisol levels recovered after 60 minutes of exposure. It was suggested that fish either became acclimatized to the noise over time or noise-induced damage to the inner ear created a threshold shift that reduced the level of perceived sound (Smith et al., 2004a).

The limited studies to date suggest that if a physiological stress response were to occur in response to exposure to airgun impulses, it would likely be of limited duration in fish. The ecological implication of increased physiological stress due to long-term noise exposure in fish has not been investigated to date. Additional research would be required to establish any relationship between sound exposure and physiological response.

4.5 Behavioural Reactions

Behavioural reactions of fish upon exposure to airgun impulses are commonly reported in the literature. All studies that conducted visual observations of fish during exposure to airgun impulses reported some form of startle response, though not in all exposed individuals. The sound intensities required to evoke a startle response were not consistent between individuals or species (even among rockfish species). One study indicated that startle response may be stronger in smaller fish (McCauley et al., 2000). In one study, startle responses were noted in some fish when the seismic vessel approached within 2500 m, with return to pre-exposure behaviour after the seismic vessel had passed beyond 1 nm (Santulli et al., 1999). In another study, intermittent startle responses (c-start) did not appear to interfere with other activities, i.e., fish continued to swim along original path (Wardle et al., 2001). Based on this review, seismic noise is expected to evoke a startle response in fish at varying thresholds which may extend some unknown distance from a vessel. The immediate biological consequences of evoking such a response in fish appear to be minimal; however, as with long-term increases in physiological stress, the ecological significance of long-term, on-going exposure of fish to sound levels sufficient to evoke a startle response is unknown.

Change in vertical position and swimming behaviour of fish was also a common response to airgun impulses. All eight studies that attempted to measure changes in vertical fish distribution noted some effect of airgun operation. Most studies indicated a downward movement of fish; however, sandeel tended to move higher in the enclosure during airgun operations (Hassel et al., 2003), while vermillion and olive rockfish demonstrated inconsistent responses -- either rising in water column or moving to bottom (Pearson et al., 1992). Changes in swimming behaviour (swimming speed, direction and orientation) were detected in four studies, generally demonstrating an increase in activity characterized as an alarm response. One study indicated a change in the day-to-night movement of reef-associated pollock (Wardle et al., 2001). It is uncertain how far from a seismic survey vessel changes in vertical position and swimming behaviour might occur and for how long, though most authors speculated that these types of responses would be temporary and generally confined to the period of sound exposure.

The extent of potential change in the horizontal distribution (dispersion) of fish upon exposure to seismic survey noise is more difficult to assess. Three studies claim to have detected an effect on the horizontal distribution of fish (Engas et al., 1996; Slotte et al., 1994; Dalen and Knutsen, 1987), while four studies claim not to have detected such an effect (Picket et al., 1994; Wardle et al., 2001; Hassel et al., 2003; IMG, 2002). Results are difficult to interpret due to the lack of received sound levels measurements, the lack of meaningful controls, the variation in species studied, and the differences in experimental conditions. All seven studies conducted experiments on different fish species except for two which studied blue whiting. While it is useful to have studies reporting on a wide range of species types (cod, haddock, pollock, sandeel, sea bass, herring, blue whiting, freshwater fish), it would also be useful to be able to demonstrate consistent results across studies of one particular species. In addition, some studies were conducted in deep water (up to 300 m water depth) while others were conducted in shallow water. The four studies that observed no effect on horizontal distribution of fish were conducted in waters less than 56 m, and one of these studies used a stationary source with no associated vessel noise to provide additional acoustic cues. Biological factors that may influence the response of fish to airgun impulses include whether they are engaged in migration, spawning or feeding, and the extent of their typical range, i.e., do they tend to move around or stay in one location. For example, the study by Wardle et al. (2001) indicated that pollock did not move away from their home reef upon exposure to seismic noise, while the study by Slotte et al. (2004) suggested that horizontal distribution of herring and whiting may have been related to the fact that they were migrating. While analysis of results by Engas et al. (1996) have been disputed by Gausland (2003) and others, this study provides the strongest evidence for horizontal dispersion of cod and haddock from a large area (74 km^2). The temporal scale of these effects were not clearly established, as monitoring was only conducted for five days after exposure and fish densities within the survey area did not returned to pre-exposure levels during this time. Given these results, the possibility of movement of fish away from a seismic survey area should not be discounted. Should this occur during spawning or other ecologically significant life-history events, population level effects may occur.

4.6 Fisheries Effects

Potential effects of seismic survey operations on commercial fisheries are of interest to Canadians. This review covers only those effects that might be directly attributable to the impacts of an airgun source on adult and juvenile fish. It does not cover the potential for spatial-temporal conflicts between seismic vessels and fisheries vessels. Neither does it consider any non-acoustic environmental impacts that might be associated with seismic survey operations. However, the potential for cumulative interactions between airgun impulses and seismic vessel noise is considered. Nine studies examining the effects of airgun operations on fishing catch and effort were reviewed. Five of these studies reported an effect and four studies reported no effect. A variety of gear types were used, including hook and line, bottom trawl, longline and gillnet. The one study using a gillnet observed no change in catch rate (La Bella et al., 1996). The results of investigations on the impact of seismic survey operations on a sandeel net fishery (Hassel et al., 2003) were considered to be inconclusive. While the average distance of the fishing fleet from the survey area did appear to increase during seismic operation, it is not evident that this was a result of changes in fish distribution. Reporting of landings rather than catch also complicates analysis, especially since several days after seismic operations were holidays and catch may have been landed outside the country. While catch rates *may* have decreased in the days immediately following seismic operations, they appear to have returned to normal soon after. Again, it is not clear that changes in landings during the study period reflected any direct impact of seismic operations. Analysis of logbooks of a hook and line sea bass fishery did not indicate declines in overall catch rate during a 5 month seismic operation (Picket et al., 1994). Impacts on trawling ranged from reductions in cod and haddock catch by ~70% (Engas et al., 1996) and reductions in cod bycatch of shrimp trawls by 79-83% (Lokkeborg and Soldal, 1993) to increases in demersal fish catch by 290% (Dalen and Knutsen, 1987) and increases in cod bycatch of a saithe trawl by 300% (Lokkeborg and Soldal, 1993). Impacts on longline catch ranged from reductions in cod catch by 55-80% (Lokkeborg, 1991), average reductions of rockfish catch by 53% (Skalski et al., 1992) to slight increases in cod catch within the immediate survey area (Engas et al., 1996). The likelihood of observing an increase or decrease in catch rate was suggested to depend upon the location of the fishing activity relative to the seismic survey and on the time between exposure and catch. For example, trawl catches of groundfish may initially increase as fish move vertically towards the seafloor and then decrease as they move horizontally out of the survey area. Linkages made between changes in catch rates and changes in fish behaviour are not definitive. However, research conducted by Skalski et al. (1992) on effects of airgun exposure to catch rates of rockfish, which detected average declines in longline catch by ~53%, was supported by previous research by Pearson et al. (1992) on behavioural effects, which indicated that rockfish tended to respond to seismic noise by changing their vertical distribution and swimming behaviour rather than by horizontal dispersion. In this case, the conclusion that reduced catch rates were a result of decreased responsiveness to baited hooks seems reasonable. Given these results, the possibility of impacts to fisheries catch rates near or within a seismic survey area should not be discounted. If effects on fisheries do occur, it may be difficult to predict whether increases or decreases in catch will occur, how long these effects may last and to what distance from a seismic survey area.

5.0 DATA GAPS

This literature review found that only a limited number of studies have been conducted on the impacts of airgun impulses on adult and juvenile fish. Research on physiological and other sub-lethal effects of fish to low frequency, impulsive noise is particularly lacking. No research has been conducted on potential masking effects of seismic airgun operations on fish communication or navigation. No information is available on the influence of seismic noise on the migratory behaviour of fish. No long-term studies have been conducted on the implications of exposure of adult or juvenile fish to recurrent (e.g., yearly) seismic airgun operations or on impacts of increased anthropogenic noise in the marine or freshwater environments in general. As a result, there is no basis upon which to assess if delayed mortality, morbidity or other chronic effects (e.g., serious pathological, reproductive, or behavioural effects) may have ecological significance under certain conditions, including exposures of long duration, repeated exposures over time or exposure during sensitive life-history events (e.g., spawning or migration).

6.0 CONCLUSIONS

Based on this review, there is considered to be a high probability that some fish within the general vicinity (i.e., 100s of meters) of a seismic survey operation will exhibit startle responses, changes in swimming speed or direction, and/or changes in vertical distribution, with recovery likely within minutes to hours after exposure. There is a lower but still reasonable probability that seismic surveys will influence the horizontal distribution/dispersion and catchability of some fish under certain conditions (e.g., during migration of pelagic fish). If horizontal dispersion does occur, impacts are more likely to be observed over greater distances (i.e., kilometers) and for a longer duration (i.e., days).

Seismic surveys are considered unlikely to result in immediate mortality of fish; however, sublethal physical damage and physiological impairments may occur within close proximity (i.e., 10s of meters) to an airgun source and could potentially result in delayed mortality or chronic effects. More work is required to assess the intensity of sound levels or distance from a seismic source required to produce these types of effects. The potential for seismic surveys to disrupt communication, including sounds necessary for reproduction, and other sound-dependant activities of fish is essentially unknown, as is the long-term ecological significance of impacts described above.

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Appendix A – Species List: Common and Scientific Names

American shad	*Alosa sapidissima*
Arctic cisco	*Coregonus autrumnalis*
Atlantic salmon	*Salmo salar*
black rockfish	*Sebastes melanops*
black tipped cod	*Epinephelus fasciatus*
bluegill sunfish	*Lepomis macrochirus*
blue rockfish	*Sebastes mystinus*
blue whiting	*Micromesistius poutassou*
bocaccio	*Sebastes paucispinis*
broad whitefish	*Coregonus nasus*
brown trout	*Salmo trutta*
burbot	*Lota lota*
chilipepper	*Sebastes goodei*
chinamen rock cod	*Epinephelus rivaltus*
cod	*Gadus morhua*
coho salmon	*Oncorhynchus kisutch*
cusk	*Brosme brosme*
eel	*Anguilla anguilla*
European sea bass	*Dicentrarchus labrax*
flathead chub	*Platygobio gracilis*
flathead minnow	*Pimephales promelas*
gizzard shad	*Nematalosa vlaminghi*
goldfish	*Caraccius auratus*
great silversmelt	*Argentina silus*
Greenland halibut	*Reinhardtius hippoglossoides*
greenspotted rockfish	*Sebastes chlorostictus*
haddock	*Melanogrammus aeglefinus*
hake	*Merluccius merluccius*
herring	*Clupea harengus*
lake chub	*Couesius plumbeus*
lantern fish	*Mycotophidae sp.*
lesser sandeel	*Ammodytes marinus*
ling	*Molva molva*
long finned rock cod	*Epinephelus quoyanus*
longnose sucker	*Catostomus catostomus*
mullet	*Mugil cephalus*
northern anchovy	*Engraulis mordax*
northern pike	*Esox lucius*
Norway pout	*Trisopterus esmarlii*
olive rockfish	*Sebastes serranoides*
oscar	*Astronotus ocellatus*
pearl dace	*Margariscus margarita*
pink snapper	*Chrysophrys auratus*
plaice	*Pleuronectes platessa*
pollock	*Pollachius virens*
rainbow trout	*Salmo gairdneri*
saithe	*Gadus virens*
silver bream	*Acanthopagrus butcheri*
silvery cod	*Gadiculus argenteus thori*
slimy sculpin	*Cottus cognatus*
sole	*Solea solea*
spangled emperor	*Lethrinus laticaudis*
Spanish flag	*Lutjanus carponotatus*
tilapia	*Oreochromis niloticus*
trout-perch	*Percopsis omiscomaycus*
trumpeter	*Pelates sexlineatus*
twaite shad	*Alosa fallax*
vermilion rockfish	*Sebastes miniatus*
walleye	*Stizostedion vitreum*
western butterfish	*Pentpodus vitta*
western dhufish	*Glaucosoma hebraicum*
white trevally	*Pseudocaranx dentex*
whiting	*Merlangius merlangus*
wrasse	*Stethojulis strigiventer*
yellowtail rockfish	*Sebastes flavidus*

Appendix B – Summary of Studies using Airgun Sources

Only portions of experiments related to adult and juvenile fish are summarized here. References are listed in alphabetical order by first author. All dB levels are relative to 1 μPa.

Bjarti, T. 2002. An experiment on how seismic shooting affects caged fish, Faroese Fisheries Laboratory (University of Aberdeen).		
Study Information		
Study Type	a) Experimental, b) Opportunistic	
Purpose	To determine if a seismic survey would harm fish in a nearby fish farm.	
Species	Rainbow trout (*Salmo gairdneri*) and Atlantic salmon (*Salmo salar*)	
Location	Faroe Islands	
Timing	June 3-6, 2002	
Conditions	Water temp of 8.4°C, strong tidal currents, water depth of 25-30m, ambient noise up to 124 dB peak to peak.	
Methodology		
Experimental Design	a) Rainbow trout of average weight 3.5 kg were contained in a fish cage with a 30m diameter and net depth of 12m. Salmon smolts (n=200) with average weight of 50 g were transferred from a freshwater smolt rearing station to a small cage with diameter of 2m and depth of 2.5m. This cage was anchored 5m from the rainbow trout cage. Equipment used to monitor sound pressure and fish behaviour was deployed from a boat between cages; all equipment was run from batteries to avoid noise from engines. Airguns were towed at 3m depth with towing speed of 2 knots with shots fired intermittently from 4000m to within 150m of the cages. Fish behaviour was monitored with two underwater video cameras. Behaviour was assessed by five independent observers. b) Log data from a long-line vessel that was fishing near the study area, including fishing area, number of hooks per day and catch, was also analyzed. The vessel fished for 15 days between May 17 – June 14, including 3 days during airgun operations. Catch was primarily cod and haddock.	
Analysis	a) Observer results were combined and summarized. No statistical analysis. b) Catch in grams per hook per day was graphed and assessed visually.	
Exposure Regime		
Source	# airguns: 4 total volume: 130 cui (110 bar)	shot interval: 10 sec source level: ~ 229 dB @ 1m
Distance to Source	a) 150-4000m, b) within 6-7 km (3-4nm)	
Received Levels	142 dB_{p-p} at 4000m and 186 dB_{p-p} at 150m (measured).	
Exposure Duration	124 sound pulses over three days	
Results		
Physical	No mortality observed.	
Behavioural	No extreme avoidance response observed. On 8 of the 124 shots, some reaction was deemed to take place in response to seismic noise (>148 dB re 1 μPa p-p). Both trout and salmon reacted, with salmon reacting at slightly higher sound levels (>167 dB). Patterns relating reaction to received sound levels were not obvious to researchers. Trout fed normally after exposure.	
Fisheries-related	Seismic noise was not considered to have impacted fishing success. Catch rates during seismic operations were similar to, though on the low end of, previous days rates. Catch rates 2-8 days following seismic operations were higher than previous catch rates. Catch rates trends from may have been unrelated to seismic operations.	
Conclusions of Report	Sound levels of 148-186 dB re 1 μPa peak to peak pressure from an airgun array resulted in minimal behavioural reaction of rainbow trout and Atlantic salmon. These movements were difficult to distinguish from normal behaviour.	

Chapman, C.J. and Hawkins, A.D. 1969. The importance of sound in fish behaviour in relation to capture by trawls. FAO Fisheries Report 62(3): 717-729.		
Study Information		
Study Type	Experimental	
Purpose	Not described	
Species	Whiting (*Merlangius merlangus)*, 20-35 cm	
Location	Loch Torridon, Scotland.	
Timing	Not described	
Conditions	Water depth of 50 fathoms (91m).	
Methodology		
Experimental Design	A research ship was anchored over a large echo-trace, extending from 15-30 fathoms (27-55m) deep. This trace was fished with hand-lines, and a large number of whiting were obtained. An airgun was then fired intermittently for short periods over about an hour. Changes in fish distribution were recorded on echo-sounder charts.	
Analysis	Echo-sounder charts were examined for changes in vertical distribution of fish.	
Exposure Regime		
Source	# airguns: 1	shot interval:
	total volume:	source level: [~220 dB @1m][1]
Distance to Source	0-91m	
Received Levels	Not measured. 192-185 dB from 25-55m using estimated source level and assuming spherical spreading, 20logR.	
Exposure Duration	1 hour	
Results		
Behavioural	When airgun pulses were initiated, whiting showed a sudden downward movement, forming a more compact layer below 30 fathoms (55m, 192 dB re 1 µPa peak pressure[2]. After about an hour, fish appeared to habituate to the sound as evidenced by a period during which fish steadily ascended. Fish continued to rise in the water column when the air gun was switched off. When the airgun was fired again, another downward response was observed.	
Conclusions of Report	Fish can react to sounds, particularly where they are of high amplitude, low frequency, and are intermittent.	

[1] as estimated by Turnpenny and Nedwell (1994).

Dalen, J. and Knutsen, G.M. 1987. Scaring effects on fish and harmful effects on eggs, larvae and fry by offshore seismic explorations. Pp.93-102. In. Merklinger, H.M. (ed) Progress in underwater acoustics. Plenum Press: New York.	
Study Information	
Study Type	Experimental
Purpose	To study the behaviour and distribution of fish along the path of a seismic survey vessel.
Species	a) Demersal fish: saithe (*Gadus virens)*, cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus)*, whiting (*Merlangius merlangus)*, great silversmelt (*Argentina silus*), ling(*Molva molva*) and cusk(*Brosme brosme*). Blue whiting (*Micromesistius poutassou*). Small pelagics: Norway pout (*Trisopterus esmarlii*), lantern fish (*Mycotophidae sp*.), silvery cod (*Gadiculus argenteus thori*) and herring(*Clupea harengus*) b) cod
Location	North Sea
Timing	June 1984
Conditions	Water depths ranging from 100 – 300 m.

Methodology				
Experimental Design	a) Prior to seismic surveying, the survey area and surrounding waters were acoustically mapped using echo-sounding and sonar. Twelve trawl stations were sampled to identify species composition and to relate soundings to three species groupings (demersal, blue whiting and small pelagics). The seismic program began on June 16 and lasted for ~1 week. On the 4th day of exposure, three comparative trawl stations were conducted. One station was sampled before and two stations immediately after the seismic vessel acquired an adjacent line. Several attempts were made to acoustically monitor changes in distribution as the seismic vessel passed within 150-300m of a stationary observation vessel; however, ship noise and unfavourable fish distributions provided inconclusive results. During the last 18 hrs of the seismic program, the survey area and surrounding waters were acoustically mapped once again. b) Eggs, larvae and fry of cod were placed in plastic bags and transferred to the study area. Large fry were placed in 40 cm^3 net enclosure and lowered with sound source to 4 m from sea surface. The distance between sound source and fry was varied from 1 to 10m. Control fish were treated similarly except for exposure. Fry were dissected for morphological changes upon death or after 7 days. Only results for fry are reported.			
Analysis	a) Seismic survey area was divided into 12 regions for statistical analysis using one-sided binomial test and nonparametric one-sided test. Raw data and quantitative analysis were not provided for comparative trawl experiments or analysis of distribution in surrounding waters.			
Exposure Regime				
Source	# airguns:	a) 40, b) 1	shot interval:	10 sec
	total volume:	a) 4752 cui, b) 640, 8610 cui (2000 psi)	source level: (dB @1m)	a) 249.9 b) 222.0, 231.0
Distance to Source	b) 1-10m			
Received Levels	a) ~ 210, 204 and 200 dB at 100, 200 and 300 m respectively if spherical spreading, 20logR, is assumed. b) ~ 202 dB at 10 m from 222 dB source and 211 dB at 10m from 231 dB source if spherical spreading, 20logR, is assumed.			
Exposure Duration	a) ~ 1 week			
Results				
Physical	b) No mortality observed upon exposure to airguns.			
Behavioural	a) Demersal fish – Comparison of average echo abundance for the seismic survey area prior to exposure vs. after exposure indicated significant ($p < 0.05$) reduction in abundance by 36%. Blue whiting – Comparison of average echo abundance for the seismic survey area prior to exposure vs. after exposure indicated non-significant ($p > 0.05$) reduction in abundance by 54%. Small pelagics – Comparison of average echo abundance for the seismic survey area prior to exposure vs. after exposure indicated non-significant ($p > 0.05$) reduction in abundance by 13%. Abundance was low throughout survey. b) Feeding success of fry was not significantly different between control fish and those exposed to 640 cui airgun. Fry (110 days) had some problems with balance upon exposure to 640 and 8610 cui airguns, but recovered after a few minutes. Exposure to watergun at 6m resulted in some loss of balance.			
Fisheries-related	a) Demersal fish – Number of demersal fish caught in comparative trawl sets increased by 34% and 290% after exposure to airguns.			
Conclusions of Report	Changes in the behaviour of fish and their overall distribution can result from exposure to seismic sound. Demersal fish appeared to move towards the ocean bottom, while pelagic fish appeared to migrate out of the area. No significant physical effects were observed upon exposure of cod fry to airgun			

	sources at close range, though some problems with balance were observed.
Related Papers	Dalen and Raknes (1985a, 1985b)

Engas, A., Løkkeborg, S., Ona, E., and Soldal, A.V. 1996. Effects of seismic shooting on local abundance and catch rates of cod and haddock. *Can. J. Fish. Aquat. Sci.* 53:2238-2249.				
Study Information				
Study Type	Experimental			
Purpose	To investigate the effects of seismic noise on catch rates of cod and haddock, and to establish how far and long these effects extend.			
Species	Cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus)*			
Location	North Cape Bank, north of Norway			
Timing	May 1992			
Conditions	Water depth of 250-280m.			
Methodology				
Experimental Design	Fish abundance was measured with longlines, trawls (60-67 sets) and echosounders for 7 days prior to seismic surveying, during the 5 days of seismic surveying, and for 5 days afterwards within an observation area of 74 x 74 km. Acoustic mapping was conducted in a concentric pattern out to a radius of 37 km from the centre of the survey area. Trawling followed a similar plan. Longlines (3900 m) were set at various distances and hauled in daily. Total catch was 20 tons of cod and 4.5 tons of haddock, which was 3% of total biomass measured acoustically. Samples of fish from trawls and longlines were analyzed for stomach contents. During 5 days of seismic surveying within a survey area of 5.6 x 18.5 km, 36 seismic lines were conducted. Lines were 10 nm long with a distance of 125 m between them.			
Analysis	Multifactor analysis of variance, time series methods and intervention analysis.			
Exposure Regime				
Source	# airguns:	18	shot interval:	10 sec
	total volume:	5000 cui	source level:	253 dB ± 3 dB @1m 248.7 (65° off axis)
Distance to Source	Study area of 74 km^2 surrounding a seismic survey area of 5.6 x 18.5 km.			
Received Levels	Not measured. [205 dB at seafloor, 178 dB at 18 km][1]			
Exposure Duration	Five days			
Results				
Behavioural	Acoustic density of fish decreased by 45% during exposure. After exposure, fish density decreased by a further 19%. Lowest densities occurred within the seismic survey area. After reductions occurred, there was a gradual smoothing of horizontal distribution across the study area. Pelagic biomass was affected more (reduced by 47%) than benthic biomass (reduced by 39%). Large fish (>60 cm or >2 kg) were more affected than small fish. No change in stomach content was observed. Ignoring bait, the degree of stomach fullness was low throughout the study period. Between 91-95% of cod in trawls and 73-79% of cod in longlines had empty stomachs (Engas et al. 1993).			
Fisheries-related	Trawl and longline catches of cod and haddock were significantly higher before exposure than during or after exposure ($p<0.001$). Trawl catch of cod was reduced by 69% in the seismic survey area and 45-50% outside the survey area. Trawl catches of haddock decreased by 68% within the seismic survey area, 56% at 1.9-5.6 km and 13-17 km from the survey, and 71% at 30-33 km from the survey. No increases in catch were observed within 5 days. Longline catch rates were reduced by 45% in the survey area, 16% at 1.9-5.6 km from the survey and 25% at 13-17 km from the survey. No reductions occurred at 30-33 km from the seismic survey area. Longline catches of cod tended to increase after exposure, except at the furthest point where catches declined.			

	Catches of haddock were reduced by 50% over that entire study area during exposure, with 67% reductions in the seismic survey area. Statistical tests on time and distance effects were significant in 6/8 cases. The interaction term (time by distance) was not significant in 3/4 cases. The study area and duration were thought to be insufficient to capture the full extent of effects.
Conclusions of Report	Seismic airgun operations can affect fish distribution and cause trawl and longline catch rates of cod and haddock to fall both within the immediate seismic survey area and in the surrounding area. Reductions appeared to be more pronounced for large than for small fish.
Related Papers	Engas et al. (1993)

[1]as estimated by Davis and Thomson (1999).

Falk, M.R. and Lawrence, M.J. 1973. Seismic exploration: its nature and effect on fish. Fisheries and Marine Service, Resource Management Branch, Fisheries Operations Directorate: Technical Report CENT-73-9.				
Study Information				
Study Type	Experimental			
Purpose	To study effects that seismic energy sources commonly used in the Northwest Territories have on fish.			
Species	Young coregonids (7-10 cm), including Arctic cisco (*Coregonus autrumnalis*)			
Location	Middle Channel of the Mackenzie River Delta, NWT.			
Timing	Not described			
Conditions	Water depth 3-6 m. Mud bottom.			
Methodology				
Experimental Design	Fish were collected from streams close to study area and held for 48 hours to allow recovery from stress. One hour before exposure, fish were placed in cages positioned at either 0.6, 1.5, 3 or 3.4 m (2, 5, 10 or 11 feet) from the airgun. After firing one shot of the airgun (except for 1 trial at 0.6 m), fish were retrieved and categorized as alive, dead or in stress. They were then taken to shore for length measurements and gross external and internal examinations.			
Analysis	Results were tabulated; no statistical analysis conducted.			
Exposure Regime				
Source	# airguns:	1	shot interval:	10-15 sec
	total volume:	300 cui (2000-2200 psi)	source level:	[230 dB @ 1m][1]
Distance to Source	0.6 - 3.4 m			
Received Levels	Not measured. 234 dB at 0.6 m and 219 dB at 3.4 m using estimated source level and assuming spherical spreading, 20logR.			
Exposure Duration	Single impulse or four impulses (1 trial at 0.6 m).			
Results				
Physical	No mortality of experimental fish was observed. No extraneous mortalities were observed in Mackenzie River within 16 km of airgun experiment. 2 of 15 fish within 3-3.4 m of airgun showed signs of stress but no overt signs of physical damage. 2 of 14 fish with 0.6-1.5 m of airgun showed signs of damage to swim bladder. No damage observed in fish exposed to multiple impulses.			
Conclusions of Report	The lethal radius of the airgun was calculated to be between 0.6-1.5 m (2-5 ft), which would be 226 – 234 dB re 1 μPa using estimated source level and assuming spherical spreading, 20logR.			

[1] as estimated by Turnpenny and Nedwell (1994).

Hassel, A., Knutsen, T., Dalen, J., Løkkeborg, S., Skaar, K., Ostensen, O., Haugland, E.K., Fonn, M., Hoines, A. and Misund, O.A. 2003. Reaction of Sandeel to Seismic Shooting: A Field Experiment and Fishery Statistics Study. Institute of Marine Research, Bergen, Norway.			
Study Information			
Study Type	Experimental		
Purpose	To determine if lesser sandeel would react to seismic noise.		
Species	Lesser sandeel (*Ammodytes marinus*)		
Location	Diana grounds, Southern North Sea		
Timing	May 2002		
Conditions	Water depth of 54-56m.		
Methodology			
Experimental Design	Sandeels were trapped in enclosures and monitored using underwater video cameras before, during and after exposure to a seismic survey. The enclosures were large enough to allow sandeels to swim freely and were open at the bottom so they could bury into the substrate. Three enclosures were placed in the centre of a 10 x 10 km seismic survey area, and three were placed outside the survey area. One-two weeks before seismic surveying started, echosoundings, grab samples and ROV were used to determine that sandeel were present in the study area. The enclosures were then lowered to the bottom where they penetrated about 5-8 cm and trapped resident sandeels. Acoustic surveys were conducted in the seismic survey area 2 days before, 2 days after and 4 days after exposure. The seismic survey was composed of 33 lines (10 km each) separated by 300 m. No lines went directly over fish enclosures.		
Analysis	Fisheries catch data were obtained from the Norwegian Directorate of Fishery. The landed catch from the regions closest to the survey area were analysed on a day-by-day basis and for 7 days periods to reveal possible change in catch rates before, during and after exposure. No statistical analysis of results.		
Controls	One enclosure was placed inside the seismic survey area but was retrieved prior to seismic surveying. Two enclosures were placed outside the seismic survey area in 51 m water depth. Initial control fish numbers were low, so were supplemented with additional trawl caught sandeels.		
Exposure Regime			
Source	# airguns: 31 (3 inactive)	shot interval:	
	total volume: 3090 cui (2000 psi)	source level: ~256.1 dB @ 1m	
Distance to Source	~60 - 7000m (center of a 10 km^2 survey area)		
Received Levels	Not measured. ~221 dB at 54 m (water depth), assuming spherical spreading (20logR). Note that no seismic lines passed directly over enclosures.		
Exposure Duration	Three days		
Results			
Physical	No direct lethal effects observed. Mortalities similar between control and experimental groups; caused by extreme handling stress and poor design.		
Behavioural	Approach of the seismic vessel resulted in slight increase in tail beat frequency. As vessel moved away, tail beat decreased. Fish continued to swim calmly. During survey, many individuals showed startle response, i.e. bending of body and fleeing out of sight. No clear relationship was established between startle response and distance to seismic vessel, though there was an overall increase in the frequency of startle responses for lines closest to cage. After shooting, fish calmed down and only one startle response was observed over 160 min. Fish remained higher in cage during shooting. A group of sandeels was observed swimming outside the cages on day 3 of shooting. These appeared unaffected.		
Fisheries-related	The average distance between fishing vessels and the survey area increased during and after use of airguns, but this may have been unrelated to seismic		

	activity. Two days after exposure, sandeel landings declined, though this may have been due to holiday closure with catch potentially landed outside the country. From day 3, landings increased for a few days, followed by a general decline until day 14 when landings increased to pre-exposure levels.
Conclusions of Report	Sandeels reacted slightly to airgun impulses but did not bury in the sand and returned to normal behaviour after impulses ceased. Mortalities of test and control fish were most likely due to handling stress and injury. The seismic survey did not cause declines in acoustic abundance of fish in the area, and increases in acoustic abundance were likely due to migration of sandeel and other pelagics through the study area.

Holliday, D.V., Piper, R.E., Clarke, M.E. and Greenlaw, C.F. 1987. The effects of airgun energy release on the eggs, larvae, and adults of the northern anchovy (*Engraulis mordax*). American Petroleum Institute, Washington, DC. Tracer Applied Sciences.				
Study Information				
Study Type	Experimental			
Purpose	The primary objective of this study was to examine the effects of seismic noise on anchovy eggs and larvae; however, a few tests on adults were conducted.			
Species	Northern anchovy (*Engraulis mordax*)			
Location	California			
Timing	a) Nov 1985, b) Apr-Jun 1986			
Conditions	Relatively flat shelf with depth of ~30m.			
Methodology				
Experimental Design	Adult northern anchovy were randomly divided into tests and controls, lowered to test depths and exposed to multiple (7 – 71) seismic impulses which increased and then decreased in amplitude to simulate passing of a seismic array. Controls were treated similarly except for exposure. Samples were then dissected for examination of swimbladders and otoliths. One series of tests were conducted in November at sea surface and at a test depth of 11 m with single airguns. Another series of tests were conducted in June at a test depth of 9.5m with a four airgun seismic array. Both “groomed” fish, i.e. laboratory cared for and fed (mean length 105.2mm), and “ungroomed” fish from a bait barge (mean length 95.8mm) were tested.			
Analysis	Insufficient replicates were conducted in November to allow for determination of confidence levels. Sufficient replicates were used in June so that confidence intervals and significance of results could be determined.			
Exposure Regime				
Source	# airguns:	a) 1, b)4	shot interval:	10 sec
	total volume:	a) 10, 40, 120, 300 cui b) 1200 cui	source level:	up to 2000 psi
Distance to Source	1.5-3m			
Received Levels	a) 215, 218, 222, 223 dB, b) 234 dB			
Exposure Duration	a) 29-71 impulses, b) 7 impulses			
Results				
Physical	November results: Ungroomed fish demonstrated greater swimbladder damage than controls with only 57% of those exposed to 0.84 bars (surface) intact vs. 86% of controls and 71% of those exposed to 1.35 bars (11m) intact vs. 100% of controls. Groomed fish demonstrated no swimbladder damage at 0.84 bars (surface) or 1.30 bars (11m); however, only 33% of swimbladders were intact after exposure to 1.78 bars as compared to 86% of controls. No confidence intervals are available for these results. June results: Only 27% of swimbladders were intact after exposure to 4.92 bars as compared to 89% of controls (p=0.01).			

	While November results indicated a trend toward greater damage in exposed otoliths than in controls, lack of replicates limits confidence in these results. June results with replicates indicated no significant difference between exposed and control otoliths.
Conclusions of Report	Ungroomed adults were found to be more susceptible to swimbladder and otolith damage than were groomed (generally healthier) adults. In general, there was more damage to fish held immediately under the ocean surface than to those held near 10m.

<table>
<tr><th colspan="5">IMG-Golder Corp. 2002. Behavioural and Physical Response of Riverine Fish to Airguns. Prepared for WesternGeco, Calgary Alberta.</th></tr>
<tr><td>Study Information</td><td colspan="4"></td></tr>
<tr><td>Study Type</td><td colspan="4">a) Experimental, b) Monitoring</td></tr>
<tr><td>Purpose</td><td colspan="4">a) To examine physical effects of seismic noise on caged freshwater fish.
b) To address concerns of potential disturbance such as “fish herding” in front of the seismic vessel during firing of the airgun array.</td></tr>
<tr><td>Species</td><td colspan="4">Freshwater fish: 2 burbot (Lota lota), 17 flathead chub (Platygobio gracilis), 36 longnose sucker (Catostomus catostomus), 13 northern pike (Esox lucius), 126 pearl dace (Margariscus margarita), 2 slimy sculpin (Cottus cognatus), 8 trout-perch (Percopsis omiscomaycus) and 1 walleye (Stizostedion vitreum).</td></tr>
<tr><td>Location</td><td colspan="4">Mackenzie River</td></tr>
<tr><td>Timing</td><td colspan="4"></td></tr>
<tr><td>Conditions</td><td colspan="4">a) Water depths were relatively shallow, ranging from 3-5 m at the position of the fish enclosures.</td></tr>
<tr><td>Methodology</td><td colspan="4"></td></tr>
<tr><td>Experimental Design</td><td colspan="4">a) 196 fish were caught, representing 14 of the 30 commonly occurring freshwater species of the Mackenzie river. Fish were equally distributed by species and size in enclosures (Gee minnow trap and PVC/plastic mesh cage) placed 2, 85, 446 and 3000 m from two stationary airgun arrays suspended 2.5 m in the water. Fish were exposed to the airgun ramp-up and then a 1 min period at full power. Observations continued for 48 hours after exposure. Eighteen of the fish used in the cage test were sacrificed for hystopathological investigation of sub-lethal effects. Trial was repeated twice and included a control site which only experienced background levels of noise (3000m away).
b) Scout boats ran vertical and horizontal transects to map fish distributions before, after and during airgun activity using vertical and horizontal fish profiling with dopler sonar (fish finders). A total of 10 transects ran perpendicular to the river in the three study locations. Each transects was run five times: pre-airgun ramp-up (control: 4 hrs before), 2 hrs before the survey, directly in front of the vessel, directly behind the vessel, and well after the survey. Fish density and distribution data were assessed.</td></tr>
<tr><td>Exposure Regime</td><td colspan="4"></td></tr>
<tr><td>Source</td><td># airguns:</td><td>array</td><td>shot interval:</td><td>15-20 sec</td></tr>
<tr><td></td><td>total volume:</td><td>1500 cui (2000 psi)</td><td>source level:</td><td>230 dB_{o-p} @ 1m</td></tr>
<tr><td>Distance to Source</td><td colspan="4">a) 2-3000m</td></tr>
<tr><td>Received Levels</td><td colspan="4">a) Peak pressure: 224 dB at 2 m, 193 at 85 m and 169 at 446 m. Root mean square: 204 dB at 8 m, 178 at 85 m and 159 dB at 446 m (measured).</td></tr>
<tr><td>Exposure Duration</td><td colspan="4">a) 5 minute ramp-up, followed by one minute at full volume.</td></tr>
<tr><td>Results</td><td colspan="4"></td></tr>
<tr><td>Physical</td><td colspan="4">a) No mortality of caged fish attributable to the seismic program within a 48 hour holding time. Some fish in the enclosure nearest the airgun array were temporarily stunned, but recovered within a ½ hour after exposure. Four fish from cages exposed to the lowest sound levels died due to handling stress. Examination of hearing and internal structures showed no difference between</td></tr>
</table>

	fish exposed to airgun at various distances and fish held at the control site. None of the 18 fish that were sent for histopathology had abnormalities attributable to airgun exposure. All abnormalities were attributed to artifacts from preservation, expected abnormalities in wild fish (i.e., parasitic infections) and/or artifacts from the preparation for analysis. None of the four fish that died during the 48 hr holding period had any significant abnormalities
Behavioural	b) No herding observed. Most fish stayed on original path in deepest part of channel.
Related Papers	MacGillivray et al. (2002)

Koshleva,V. 1992. The impacts of air guns used in marine seismic explorations on organisms living in the Barents Sea. Fisheries and Offshore Petroleum Exploitation 2nd International Conference, Bergen, Norway, 6-8 April 1992.			
Study Information			
Study Type	Experimental		
Purpose	To test the impacts of airguns used in Barents Sea petroleum exploration on marine organisms.		
Species	Young and mature fish (cod, *Gadus morhua*, mentioned specifically)		
Location	Ura Guba Inlet, Barents Sea		
Timing	1989 and 1990		
Experimental Design			
Methodology	Test organisms were suspended in cages at 0.5 m, 1 m and 2 m from the airgun. 18 series of exposures were conducted. Each was followed by tests for signs of impacts, starting with visual observations for outward signs of injury and changes in behaviour and concluding with the killing of the specimen to conduct physiological examinations. The control group consisted of specimen organisms of the same species.		
Exposure Regime			
Source	# airguns: 1, array	shot interval:	
	total volume: 1-3L, 20L	source level:	[220-240 dB @ 1m][1]
Distance to Source	0.5, 1.0 and 2.0m		
Received Levels	Not measured. 226, 220 and 214 dB at 0.5, 1 and 2 m respectively, assuming a source of 220 dB and spherical spreading (20logR). 246, 240 and 234 dB at 0.5, 1 and 2 m respectively, assuming a source of 240 dB.		
Exposure Duration	It is unclear whether organisms were exposed only once or to the full series of 18 exposures.		
Results			
Physical	Fish exposed to single airguns at 0.5m showed some internal signs of impact, but there were no fatalities. No effects were observed at 1m. More impact was observed after exposure to the full array than to isolated shots, particularly for arrays with total volumes of 5 L or more placed at 0.5m. Again, no effects were observed at or beyond 1m. Half of fish exposed to an array containing two 5 L airguns at 0.5m suffered damage to blood cells or internal bleeding. There was also evidence of injury to white blood cells, such as bubble formation in cell nuclei. In a few cases, young cod received eye injuries. No effects were observed at 1m. In young cod, there was increased inflammation of tissues as the volume increased to 3 L at 0.5m. This damage worsened over time.		
Conclusions of Report	Single airguns had negligible effects at all distances. Slightly more impact was see upon exposure to full arrays. Results were considered to be consistent with other data that suggests airguns are ecologically benign and safe for seismic exploration, but it was suggested that operating airguns over spawning grounds during spawning season be prohibited.		

[1] as estimated by Turnpenny and Nedwell (1994).

La Bella, G., Cannata, S., Froglia, C., Modica, A., Ratti, S. and Rivas, G. 1996. First assessment of effects of air-gun seismic shooting on marine resources in the central Adriatic Sea. Society of Petroleum Engineers, paper SPE 23782.	
Study Information	
Study Type	Experimental
Purpose	To test effects of seismic noise on the primary fisheries of the Adriatic Sea.
Species	primarily hake (*Merluccius merluccius)* and clupeoids [studies on European sea bass reported in Santulli et al. (1999)]
Location	Off coast of Italy, Adriatic Sea
Timing	Summer 1995
Conditions	25 miles offshore, 70-75m depth
Methodology	
Experimental Design	*Influence on trawl fishery and pelagic distribution:* A series of trawl samplings and echo-sounder observations were made prior to seismic operations. A traditional Mediterranean bottom trawl (cod-end mesh size 40 mm stretch) was used. It has a low vertical opening (1 m) and long sweep ropes with herding effect on demersal fish. All tows were done with the same course in a narrow area. Before start of seismic operation, 8 trawl samples (4 during day and 4 at night) were taken. Total catch was sorted by species and weighed. Size frequency distributions were recorded for common species (hake and Norway lobster). Relative abundance of pelagic fish (mostly clupeoids) was estimated simultaneously along the trawl path with an echo sounder (SIMRAD EK500). Data were analysed in terms of vertical segregation, slicing water column in 7 layers from bottom to 8 m below surface). During seismic operations, a total of 111.3 km were shot. The process of biological sampling was repeated once seismic operations were completed. *Influence on gill-net fishery:* Two sets of gill-nets (3,200 m with 72 mm mesh size) were set in place at dusk and retrieved at dawn, the day before and after the seismic operation. Catch was sorted by species and recorded in number and weight per unit effort.
Analysis	Catch data before and after exposure were compared with ANOVA. Length frequency distributions were compared using Kolmogorov test.
Exposure Regime	
Source	# airguns: 16 — shot interval: 25 sec total volume: 2500 cui (2000 psi) — source level: 256 dB_{o-p} @ 1m
Distance to Source	Variable
Received Levels	Not measured.
Exposure Duration	~ 12 hrs (60 nm at 5 nm/hr)
Results	
Behavioural	The total pelagic biomass over the survey area did not show significant changes before and after exposure, but a lower proportion of the total pelagic assemblage migrated to the surface layers.
Fisheries-related	No evidence of significant changes in trawl catch before and after the seismic program was observed. Catch composition appeared to be more influenced by timing (day vs. night) than by exposure to seismic noise. Length frequency distributions of hake sampled one day before and one day after seismic exposure were similar (Kolmogorov test D = 0.0419 χ^2 = 1.4159). No evidence of significant changes in gill-net catch of sole or gunard was observed.
Conclusions of Report	These experiments did not demonstrate any significant variation in trawl catches or size frequency distribution of finfish as a results of seismic survey operations. Some behavioural effects were observed in Clupeoids (change in vertical distribution).

Related Papers	Santulli et al. (1999)

Løkkeborg, S. 1991. Effects of a geophysical survey on catching success in longline fishing. *ICES (CM)* B:40.				
Study Information				
Study Type	Opportunistic			
Purpose	To study the effects on longline catches of a geophysical survey conducted during the winter fishery for cod.			
Species	Cod (*Gadus morhua*)			
Location	Off the coast of Finmark, north of Norway			
Timing	Jan 1990			
Conditions	Water depth of ~185m. Conducted during seasonal migration of cod towards spawning areas.			
Methodology				
Experimental Design	A seismic survey with a total of 32 track lines (2.5 nm each) was conducted in January 1990 off the coast of Finmark. Catch data (including position, time of set, and estimated weight of catch) of four longliners operating in the area were collected and analyzed. These data were related to the position of the seismic survey tracklines and timing of airgun discharge.			
Analysis	Significance of results not calculated by author.			
Exposure Regime				
Source	# airguns:	4	shot interval:	5 sec
	total volume:	40 cui	source level:	239 dB @ 1m
Distance to Source	Within ~15 km of survey area.			
Received Levels	Not measured. [~161 dB at 5 km][1]			
Exposure Duration	~43:25 hrs over 11 days.			
Results				
Fisheries-related	Cod catch rate reductions of 55-80% were observed for longlines set within the seismic survey area. Catch data obtained from all four longliners showed similar trends. Effects persisted for 24 hours within 5nm of the seismic survey.			
Conclusions of Report	This study indicates effects of seismic survey operations on longline catch rates. Behavioural studies (e.g. ultrasonic tagging) required to determine if such effects are due to changes in distribution or feeding motivation.			
Related Papers	Løkkeborg and Soldal (1993)			

[1] as estimated by Turnpenny and Nedwell (1994).

Løkkeborg, S. and Soldal, A.V. 1993. The influence of seismic exploration with airguns on cod (*Gadus morhua*) behaviour and catch rates. *ICES Mar. Sci. Symp.* 196:62-67.	
Study Information	
Study Type	Opportunistic
Purpose	To investigate the effects of seismic operations on the by-catch of cod in trawls for shrimp (two cases) and saithe (one case).
Species	Cod, >42 cm (*Gadus morhua*)
Location	a) Off coast of Finmark, b) near Bear Island in Barents Sea, c) at Storegga off the coast of W. Norway.
Timing	a) June 1989, b) Aug 1991, c) Apr 1991
Conditions	a) trawling for shrimp in 200-300m, b) trawling for shrimp in 200-300m, c) trawling for saithe in 150-250m. Bad weather conditions.
Methodology	
Experimental Design	With the permission of fishing vessel operators, catch data from shrimp trawlers that had been operating in the vicinity of three different seismic surveys were obtained from official catch records. The estimated weight of the

	catch, and the time and start position of each haul (generally 10-15 nm long), were noted in relation to position and timing of seismic survey tracklines. It wasn't possible to determine the exact distance between catch and sound source.			
Analysis	Catch rates before, during and after the seismic surveys were compared.			
Exposure Regime				
Source	# airguns:	a) 20, b) 40, c) array	shot interval:	
	total volume:	a) 40, b) 2660, c) 4000 cui	source level:	Not measured. [239-250 dB @ 1m][1]
Distance to Source	Hauls starting within 9.3 km (5 nm) of seismic survey			
Received Levels	Not measured. [160-171 dB re 1 µPa][1]			
Exposure Duration	a) data obtained for 2 days of a 6 day seismic survey b) data obtained for 3 days during a seismic survey c) 12 hours			
Results				
Fisheries-related	Significant ($p<0.05$) cod by-catch reductions of 79% (24 to 5 kg/towing hour average) and 83% (18 to 3 kg/towing hour) were observed within 9.3 km of two seismic survey areas (Finnmark and Bear Island surveys respectively). By-catch of cod returned to pre-shooting levels about one day after the survey ended. At Storegga, by-catch of cod increased threefold during short periods of airgun exposures (9 and 3 hours each). Catches returned to pre-exposure levels within 12 hours after the seismic operation had ended.			
Conclusions of Report	Seismic operations can significantly influence the catch rates of cod in longline and trawl fisheries. These reductions are likely due to the behavioural responses of fish to the airgun sound source, including movement downwards and then away from the survey area.			
Related Papers	Løkkeborg (1991)			

[1] as estimated by Turnpenny and Nedwell (1994).

Matishov, G.G. 1992. The reaction of bottom-fish larvae to airgun pulses in the context of the vulnerable Barents Sea ecosystem. Fisheries and Offshore Petroleum Exploitation 2nd International Conference, Bergen, Norway, 6-8 April 1992.				
Study Information				
Study Type	Experimental			
Purpose	To examine the contribution of geophysical survey operations to a decline in the distribution and abundance of commercial fish in the Barents Sea.			
Species	Cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*)			
Location	Barents Sea			
Timing	1989			
Methodology				
Experimental Design	Caged cod and plaice were exposed to a single shot of an airgun at ranges of 2 and 4m.			
Exposure Regime				
Source	# airguns:	1	shot interval:	n/a
	total volume:		source level:	[226 dB @ 1m][1]
Distance to Source	2-4m			
Received Levels	Not provided. 220 dB at 2 m and 214 dB at 4 m using estimated source level and assuming spherical spreading (20logR).			
Exposure Duration	Single shot			
Results				
Physical	Fish exposed to a single airgun discharge at 2m range were stunned for 5 min and died within 48 hrs due to extensive haemorrhaging in gills, liver, medullar oblongata and mesenecephaton. Fish held at 4m range became blind but stayed alive over a 2 week period following exposure.			

Conclusions of Report	It is suggested that airgun arrays be prohibited from use over spawning grounds during spawning activity and from other areas of larval drift.

[1] as estimated by Turnpenny and Nedwell (1994).

McCauley, R.D., Fewtrell, J., Duncan, A.J., Jenner, C., Jenner, M-N., Penrose, J.D., Prince, R.I.T., Adhitya, A., Murdoch, J. and McCabe, K. 2000. Seismic surveys: analysis and propagation of air-gun signals; and effects of air-gun exposure on humpback whales, sea turtles, fishes and squid. Australian Petroleum Production Exploration Association. Western Australia.			
Study Information			
Study Type	Experimental		
Purpose	To gauge the behavioural response and any physiological or pathological effects on caged fish from exposure to a seismic survey.		
Species	silver bream (*Acanthopagrus butcher*i), trumpeter (*Pelates sexlineatus*), trevally (*Pseudocaranx dente*x), pink snapper (*Chrysophrys auratu*s), herring (*Clupea harengus*), mullet (*Mugil cephalu*s), black tipped cod (*Epinephelus fasciatu*s), long finned rock cod (*Epinephelus quoyanu*s), chinamen rock cod (*Epinephelus rivaltus*), western butterfish (*Pentpodus vitt*a), wrasse (*Stethojulis strigiventer*), spangled emperor (*Lethrinus laticaudis*), spanish flag (*Lutjanus carponotatu*s), and dhufish (*Glaucosoma hebraicum*).		
Location	Jervoise Bay and Exmouth Gulf, Australia (Feb 97 - Nov 98)		
Timing	Mar 1996 – Oct 1999		
Conditions	Jervoise Bay: water temp. of 16-20°C, water depth of 9m with a fine, muddy bottom. Exmouth Gulf; water temp 21-23°C, water depth of 10m, enclosures held in a tidal stream with currents to 1 knot.		
Methodology			
Experimental Design	Nine experimental trials were conducted, seven in Jervoise Bay and two in Exmouth Gulf. Fish were captured or obtained from aquaculture facilities, and were acclimated in enclosure prior to trails. Enclosures were located some distance from the airgun, which was deployed from a pontoon (Jervoise) or small vessel (Exmouth). Controls were used in all experiments. Control fish were handled similarly to test fish except for size of enclosure. a) Behavioural observations and analysis: Fish were observed with a high resolution black and white video camera and colour digital video camera for 1 hour pre-exposure and 45-60 min after exposure. b) Physiological response : Blood samples for cortisol and glucose levels, and blood smears for cell counts were sampled at intervals after exposure. Samples were also taken from control fish. c) Pathology: Fixation of macula surrounding otoliths for assessment of damage to hair cells (hearing damage) using an electron microscope.		
Analysis	Modeling was also conducted on the response of fish otoliths to airgun signals.		
Exposure Regime			
Source	# airguns: 1	shot interval: 10 sec	
	total volume: 20 cui (10 MPa)	source level: 222.6 dB_{p-p}	
Distance to Source	a) 5 - 800m, b) 10-30m and 5-450m, c) 5-800m		
Received Levels	146-195 dB re 1 μPa root mean square (rms)		
Exposure Duration	Variable		
Results			
Physical	No mortality. Additional results reported in McCauley et al. (2003).		
Behavioural	Startle response (C-turn) to short range start-up or high level air gun signal (182-195 dB from 200-800m). Greater startle response observed in small fishes. Alarm response above 156-161 dB mean square pressure. Lessening of startle and alarm response over time. Increased use of lower portion of cage during airgun operations. General behavioural response of fish to move to bottom, centre of cage in periods of high air-gun exposure. Faster swimming		

	and formation of tight groups correlating with high air gun levels.			
Physiological	No significant measured stress increases which could be directly attributed to airgun exposure of 146-195 dB (rms).			
Conclusions of Report	Captive fish displayed a generic 'alarm' response of increased swimming speed, downward movement, and tightened school structure at an estimated 2-5 km from a seismic airgun source. Modeling of fish hearing predicts that at ranges of less than 2km from an airgun, a fish ear would begin a rapid increase in displacement parameters. Fish exposed to short range air gun signals showed some damage to hearing structures but no evidence of increased physiological stress response. Potential effects on fish may not necessarily translate into population scale impacts or disruption of fisheries.			
Related Papers	McCauley et al. (2003, 2000, 2001)			

McCauley, R.D., Fewtrell, J., and Popper, A.N. 2003. High intensity anthropogenic sound damages fish ears. *J. Acoust. Soc. Am.* 113:638-642.				
Study Information				
Study Type	Experimental			
Purpose	To investigate possible effects of air-gun noise on the hearing system of fishes.			
Species	Pink snapper (*Chrysophrys auratus*)			
Location	Jervoise Bay, Australia			
Timing	Not provided.			
Conditions	Average depth of 9 m.			
Methodology				
Experimental Design	Pinks snapper were held in enclosures (10 x 6 x 3 m or $1m^3$) and exposed to an airgun towed toward and away from the cage (from start up at 400-800m to 5-15m). Some of the test fish (group II) were killed 18 hours after airgun exposure, while others (group III) were killed 58 days later. Control fish (group I) were kept in the same enclosures used for experimental animals but were removed from cages and sacrificed just before exposure to airgun.			
Analysis	Fish were sacrificed and dissected. Ears were prepared and mounted for examination using a scanning electron microscope. Digital transects (images) were overlain with 25 μm gridlines and number of missing cells per 24x625 μm^2 were counted. Results were reported as holes per 10,000 μm^2. 95% confidence intervals were determined using all images per group.			
Exposure Regime				
Source	# airguns:	1	shot interval:	10 sec
	total volume:	20 cui	source level:	222.6 dB_{p-p} @ 1m
Distance to Source	5-800m			
Received Levels	< 212 dB_{p-p} at 5m.			
Exposure Duration	Four approaches towards enclosure over 1:05 hours, break of 1:12 hours then three additional approaches over 0:36 hours.			
Results				
Physical	Epithelia of group I fish (control) had appearance similar to other species, with fields of ciliary bundles distributed across the epithelia. A small number of holes, correlating with the expected location of hair cells were found in group I. Group II fish were observed to have localized dense patches of holes and "blebbing" or "blistering" on the surface of the epithelia coincident with the location of hair cells. When the number of holes/10,000 μm^2 along three transects across the epithelium were compared with group I fish, results were not significant (p>0.1, 2-tailed t-test). Group III fish showed significantly greater numbers of holes/10,000 μm^2 than group I or II fish. (p<<0.001, 2-tailed t-test) and greater areas of "blebbing". "Blebbing" was consistent with expansion of			

	the ear cell ciliary bundle surface, with eventual rupture leading to a hole. Group III fish held for 58 days after exposure continued to grow and showed no sign of disease.
Conclusions of Report	This study demonstrates that exposure to seismic airguns can cause significant damage to the ears of fishes.
Related Papers	McCauley et al. (2003, 2000, 2001)

Pearson, W.H., Skalski, J.R. and Malme, C.I. 1992. Effects of sounds from a geophysical survey device on behaviour of captive rockfish (*Sebastes spp.*). Canadian Journal of Fisheries and Aquatic Sciences 49:1343-1356.				
Study Information				
Study Type	Experimental			
Purpose	To determine the threshold at which sounds from an airgun produced a startle response or other behavioural change in captive rockfish.			
Species	Blue (*Sebastes mystinus*), black (S. *melanops*), vermilion (S. *miniatus*), olive (S. *serranoides*) and brown (S. *auriculatus*) rockfish.			
Location	Cayucos, off California coast			
Timing	Jul 13–18, 1986			
Conditions	Sheltered bay of 14m water depth, soft bottom of fine sand and silt.			
Methodology				
Experimental Design	5 behavioural trials were conducted over five days with 2-6 exposures per trial. Before each trial, rockfish were captured near rock pinnacles by trolling with lures and barbless hooks in depths from 10 to 30 m. Upon capture, swim bladders were expelled by puncturing them with a hollow needle to reduce mortality. Fish were then placed in a holding tank. Within 3 hours of capture, fish were transferred to the field enclosure and acclimated overnight. Each trial varied in the number of rockfish and their species composition. Trials began with an observation period of at least 30 min. Notes on the behaviour of fish were recorded at 2 min intervals. This observation period was followed by 2-6 (depending on weather), 10-min periods of airgun operation, during which observations were made continuously and recorded at 1-min intervals. Observations were also recorded in intervals between airgun firing. In trials 1 and 2, the sound level during each succeeding 10-min exposure was increased by bringing the vessel ~half the distance of the previous exposure (5800, 2900, 1500, 760, 350 and 185m). In subsequent trails, sound levels were varied by directing the vessel to decrease or increase its range depending on fish response (11-1760 m).			
Analysis	Graphical displays and multiple analysis were used to examine the relationship between exposure levels, changes in vertical distribution, and other responses. 4/5 trials tested sufficient fish (n>13) to provide usable results.			
Exposure Regime				
Source	# airguns:	1	shot interval:	10 sec
	total volume:	100 cui (4500 psi)	source level:	223 dB_{o-p} @ 1m
Distance to Source	11-5800m			
Received Levels	137 – 206 dB_{o-p} (measured).			
Exposure Duration	10 min exposures, 2-6 times.			
Results				
Behavioural	Rockfish species reacted to airgun sounds with alarm and startle responses. The character and extent of these responses varied with species and sound level. Startle response (flexing of body or shudder) was observed at ≥200-205 dB for black and olive rockfish. Alarm response was observed at 177-180 dB for blue and black rockfish, 186-195 dB for vermilion rockfish, and above 199 dB for olive rockfish. Blue rockfish milled in increasingly tighter schools with			

	increasing airgun levels. Black rockfish schools collapsed to bottom when airguns started where they remained unpolarized and unsynchronized. Vermilion and olive rockfish either rose in the water column and eddied at increased speed or moved closer to bottom and became almost motionless. Return to pre-exposure behaviour occurred within the 20-60 min exposure period. The general response threshold of rockfish was considered to ~180 dB, with a threshold for subtle changes in behaviour extrapolated as 161 dB.
Conclusions of Report	The general threshold for alarm response in captive rockfish was found to be about 180 dB re 1 μPa. More subtle behavioural responses may be observed at 161 dB re 1 μPa. These responses were sustained for only a few minutes and may differ in nonconfined fish.
Related Papers	Pearson et al. (1987), Skalski et al. (1992)

Pickett, G.D., Eaton, D.R., Seaby, R.M.H. and Arnold, G.P. 1994. Results of bass tagging in Poole Bay during 1992. Ministry of Agriculture, Fisheries and Food Directorate of Fisheries Research, Fawley Aquatic Research Laboratories. Laboratory Leaflet #74.				
Study Information				
Study Type	Monitoring			
Purpose	To investigate the effects of seismic shooting on inshore bass fisheries in shallow UK waters.			
Species	European sea bass (*Dicentrarchus labrax*)			
Location	Poole Bay, UK.			
Timing	Jun 1 - Oct 14, 1992			
Conditions	5-30 m water			
Methodology				
Experimental Design	From May 22 to Oct 24, 1992, 1248 European bass of commercial size were tagged and released near a proposed seismic survey area using rod-and-line. Catch log books were distributed to 12 skippers who fished in the seismic survey area. A seismic survey comprised of 17 transects with lengths of 18km was conducted from Jun 1 to Oct 14. Towing speed was 3.5 knots at a depth of 3m using two alternating arrays (characteristics described below).			
Analysis	Tag returns (including location of catch) were reported by fishermen to the Directorate of Fisheries Research and collated in the lab database. Tag returns without recapture positions were excluded from analysis. Seven log-books were completed with daily records of catch throughout the seismic survey period; 6 of these used baited hook and lines. Log book catch data was analysed using standard statistical methods.			
Exposure Regime				
Source	# airguns:	2 x 8	shot interval:	10 sec
	total volume:	1220 cui (135 bar)	source level:	[250 dB @ 1m][1]
Distance to Source	0.9 – 22.6 km (to fishing vessels)			
Received Levels	Not measured. 163-191 dB estimated using spherical spreading, which is not likely to be accurate.			
Exposure Duration	Jun 1 – Oct 14			
Results				
Behavioural	152 tags were returned between May 1992 and Sep 1993, the majority of which within 10 km of release site. Considered to indicate that there were no long-range movements of bass out of survey area.			
Fisheries-related	Average catch rate of commercial bass for 6 boats was 5.4 bass per day in May and 6.3 bass per day in Jun-Oct. Average size of bass caught remained fairly constant throughout May-Oct. Two boats had low catch rates, but were catching other fish. One boat reported 4429 undersize bass caught - high proportion of undersize catch. However, undersize fish were present on the			

	fishing marks throughout the period. Considered to indicate that catch rates were not affected.
Conclusions of Report	This study demonstrated no discernable effect of a seismic survey on local catch rates, average size of fish caught, or distribution and movement of bass in the area. This study suggests that there was no large scale migration of bass away from the seismic operation, which may have been due to the relatively shallow waters, high propagation loss, and high ambient noise.

[1] as estimated by Turnpenny and Nedwell (1994).

Popper, A.N., Smith, M.E., Cott, P.A., Hanna, B.W., MacGillivray, A.O., Austin, M.E. and Mann, D.A. 2005. Effects of exposure to seismic airgun use on hearing of three fish species. J. Acoust. Soc. Am. 117(6) 3958-3971.				
Study Information				
Study Type	Experimental			
Purpose	To investigate the effects of a seismic airgun on hearing of riverine fish.			
Species	Northern pike (*Esox lucius*), broad whitefish (*Coregonus nasus*) and lake chub (*Couesius plumbeus*)			
Location	Mackenzie River Delta			
Timing	Not described			
Conditions	1.9m water depth at the end of a fixed dock			
Methodology				
Experimental Design	Whitefish and northern pike were placed in a 1m^3 holding pen, Lake chub and young pike were placed in a galvanized Gee minnow trap, and all were held about 1m below the surface of the Mackenzie River. The airgun array was then fired 5 or 20 times. Fish were removed to a holding tank until measured for auditory brainstem response. Some were held for 24 hours to study recovery, while others were analyzed within 1.5 hours of exposure. Control fish experienced the same conditions except for exposure to seismic impulses.			
Analysis	Results tested using separate ANOVAs with treatment (control vs. exposed) and frequency as factors. Tukay's post-hoc test was used to conduct pairwise comparisons between specific frequencies when significant effects were found (Zar 1984).			
Exposure Regime				
Source	# airguns:	8	shot interval:	40 sec
	total volume:	730 cui	source level:	13.1 kPa [202 dB @ 1m]
Distance to Source	17m and 13m			
Received Levels	205.2 – 209.9 dB mean peak sound pressure level			
Exposure Duration	5 or 20 seismic pulses			
Results				
Physical	No mortality of fish held for 24 hours after exposure. No obvious morphological damage to swimbladder, eyes, gills or internal organs. No significant hearing differences between exposed and control whitefish. Statistically significant hearing loss detected immediately upon exposure of adult northern pike to 5 seismic pulses at 400 Hz, with recovery within 18 hours. No hearing loss observed in juvenile pike. Statistically significant hearing loss detected immediately upon exposure of adult lake chub to 5 and 20 seismic pulses at 200, 400 and 1600 Hz, with recovery within 18 hours. Maximum threshold shift of 25 dB obtained for 5 shots at 200 Hz, and maximum threshold shirt of 35 dB obtained for 20 shots at 400 Hz.			
Behavioural	Normal swimming behaviour upon exposure.			
Conclusions of	There are substantial differences in the effects of seismic airguns on the			

Report	hearing thresholds of various fish species. Effects appear to have a correlation to the hearing sensitivity of the fish.

Santulli, A., Modica, A., Messina, C., Ceffa, L., Curatolo, A., Rivas, G., Fabi, G. and D'Amelio, V. 1999. Biochemical response of European Sea Bass (*Dicentrarchus labrax L.*) to the stress induced by off shore experimental seismic prospecting. *Mar. Poll. Bull.* 38(12):1105-1114.				
Study Information				
Study Type	Experimental			
Purpose	To examine variations in biochemical parameters of European sea bass exposed to seismic noise, and to examine any effects on skeletal structure.			
Species	European sea bass (*Dicentrarchus labrax*)			
Location	Off coast of Italy, Adriatic Sea.			
Timing	Summer 1995			
Conditions	Average depth of 15 m, 6 km (3 nm) from the coast.			
Methodology				
Experimental Design	An experimental seismic survey was conducted along a 19 km (10 nm) transect. Acoustic and spectral analysis of noise emissions were conducted prior to and during the survey. Six groups of European sea bass in age class 0+ and six groups of age class 1+ were distributed in 2 groups of 6 m^3 metal enclosures at a density of 25 individuals/m^3. The enclosures were distributed at various distances (180, 2400, 3700, and 6500 m) from the transect. An underwater video camera was positioned at 180 m to record fish reactions. Enclosures were recovered 6 or 72 hours after exposure. Fish of 0+ age class were x-rayed. Fish of age class 1+ recovered 6 hours before and after exposure were sampled for chemical analysis. Additional fish were processed after 72 hours. Control fish were processed 6 hours before the start of the seismic survey.			
Analysis	Variance analysis was used to test for significance.			
Exposure Regime				
Source	# airguns:	16	shot interval:	25 sec
	total volume:	2500 cui (2000 psi)	source level:	256 dB_{o-p} @ 1m
Distance to Source	180-6500m			
Received Levels	Not measured. 210 dB at 180m, 204 dB at 800m and 199 dB at 2500m assuming spherical spreading, 20logR, for first 15m (water depth) and cylindrical spreading, 10logR, for rest of distance.			
Exposure Duration	~2 hrs (10nm at 5 nm/hr)			
Results				
Physical	No mortality and no modification of spinal cord morphology, no alteration, infraction or fracture of the fin rays.			
Behavioural	At 2500m, most fish swam slowly against the current, some fish showed startle response. At 800m, a larger proportion showed startle response. At 180m, fish bunched in the center of enclosure with random orientation and general increase in activity. When the vessel passed beyond 1 nm, the startle response was no longer evident and behaviour returned to normal within 1 hr.			
Physiological	*Serum analysis*: Fish examined 6 hours before and after exposure indicated changes in 1º and 2º stress response. Cortisol levels, glucose and lactate increased significantly ($p < 0.01$). Serum content of adenylates (AMP, ADP, ATP) was significantly reduced, which was most evident in ATP concentrations. Phosphate bond reserve as indicated by AEC did not show significant variation. There was a non-significant increase in cAMP. *Tissue analysis*: In both muscle and liver tissue, cortisol was significantly higher ($p < 0.05$) in fish examined 6 hours after exposure as compared to controls, but not in fish examined 72 hours after exposure. Glucose showed			

	no significant difference. Lactate was significantly higher both 6 and 72 hours after exposure but did not vary significantly with distance from exposure. In muscle tissue, AMP did not vary between trials; ADP was higher 6 hours after exposure and still higher 72 after exposure at all distances; ATP decreased significantly after exposure; and AEC values did not change significantly. In liver tissue, variation in adenylates was more consistent and was always significant ($p < 0.05$). AMP and ADP values decreased during the 72 hours, while ATP and AEC values recovered to pre-exposure levels within 72 hours. cAMP levels showed similar patterns in liver and muscle, with significant increases (more than 50%) at 72 hours after exposure. Increases appeared to correlate positively with distance.
Conclusions of Report	Exposure to a seismic source was found to generate a biochemical stress response in captive sea bass. Results indicated a typical primary and secondary stress response upon exposure to airgun impulses; however, rapid recovery was observed within 72 hours and no mortalities were reported. Macroscopic effects on skeletal apparatus were not observed.
Related Papers	La Bella et al. (1996)

Skalski, J.R., Pearson, W.H., and Malme, C.I. 1992. Effects of sounds from a geophysical survey device on catch-per-unit-effort in a hock-and-line fishery for rockfish (*Sebastes spp*.). Canadian Journal of Fisheries and Aquatic Sciences 49:1357-1365.	
Study Information	
Study Type	Experimental
Purpose	To examine the effect of sound from an airgun on the commercial hook-and-line fishery for rockfish along the California coast.
Species	Rockfish: chilipepper (*Sebastes goodei*), bocaccio (S. *paucispinis*), yellowtail (S. *flavidus*), vermilion (S. *miniatus*), and greenspotted (S. *chlorostictus*).
Location	Off California coast
Timing	Jul 19 – Aug 3, 1986
Conditions	Sheltered bay of 14m water depth, soft bottom of fine sand and silt.
Methodology	
Experimental Design	17 preliminary fishing surveys were conducted on separate rockfish aggregations to select a standard unit of effort and estimate associated variance for sample size calculations. A standard unit of effort was set at 3 setline deployments with bottom times of 20 min. In the field experiment, a ship with airgun traversed the study area either firing the airgun so that a noise level above 180 dB would reach the base of the rockfish pinnacle or firing a bubble source that produced negligible sound levels (control trial) to eliminate bias from fishing vessel operators. The seismic vessel then circled 165 m from the study area to provide continuous sound exposure while the fishing vessel deployed a set line (80 hooks baited with mackerel), did three echosounder transects and then deployed two more set lines for 20 min each. Each experiment lasted 1:25 hours. All trials were restricted to rockfish aggregations on rock pinnacles at depths between 82.3 and 182.9m. On recovery of the setlines, the catch was examined and the species and size of each fish was recorded by hook number. Fish were sorted by market value and weighed on a deck scale upon completion of each trial.
Analysis	Covariance analysis was used to analyze the total catch of all rockfish and the catches of the five most abundant species.

Exposure Regime				
Source	# airguns:	1	shot interval:	10 sec
	total volume:	100 cui (4500 psi)	source level:	223 $dB_{o\text{-}p}$ @ 1m
Distance to Source	82-183m			
Received Levels	186-191 dB peak pressure at base of rockfish aggregation (measured).			
Exposure Duration	1 hr 25 min.			
Results				
Behavioural	The mean change in aggregation height was significantly different between control and emission trials after adjustment for species composition. Under control conditions, there was no tendency for change in height when aggregations were composed of demersal species (e.g. vermilion rockfish). As the proportion of pelagic species (e.g. chilipepper) increased, the aggregation height increased by 24% between preoperational and operational phases of fishing. During emission trials, there was an overall decrease in aggregation height irrespective of species composition. With all demersal species, the height decreased by 26% between phases. With all pelagics, height decreased by 8% between phases.			
Fisheries-related	A significant decline (52.4%, α = 0.016) in mean total catch of rockfish was found under emission conditions after adjustment to a common depth. At a depth of 109.7 m, control trials had a mean catch of 34 fish while emission trials had a mean catch of 16 fish. For the five most abundant fish, 3 species (chilipepper, bocaccio and greenspotted rockfish) showed significant declines in catch during emission trials after adjustment to a common depth. After adjustment to an average mean depth of 109.7 m, control trials had an average cash value of $51.33 while emission trials yielded a mean cash value of $25.78. This difference represents a decline of 49.8%.			
Conclusions of Report	Sound exposure from a seismic survey may result in changes to rockfish behaviour and catchability. The potential effects on rockfish catchability from detailed (3D) seismic surveys with close tracklines warrant concern.			
Related Papers	Pearson et al. (1987, 1992)			

Slotte, A., Hansen, K., Dalen, J. and One, E. 2004. Acoustic mapping of pelagic fish distribution and abundance in relation to a seismic shooting area off the Norwegian west coast. *Fish. Res.* 67:143-150.	
Study Information	
Study Type	Experimental
Purpose	To map the pelagic fish distribution and abundance within Ringhorne Dome and surrounding waters, and to investigate whether or not a seismic survey had any effect on fish distribution and abundance.
Species	Herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*) and mesopelagics
Location	Ringhorne Dome, Norwegian Sea
Timing	April 1999
Conditions	Herring and blue whiting engaged in a large-scale feeding migration. Water depth not provided.
Methodology	
Experimental Design	Pelagic fish within seismic area and surrounding waters up to 30-50 km away were mapped with a 38 kHz echo sounder, connected to the Bergen Echo Integrator Postprocessing System (BEI). Acoustic surveys took place during the seismic program, generally in periods when airguns were not active. Acoustic surveys were not conducted prior to the seismic program.

Analysis	Anova was used to test for effect of area as an independent factor on acoustic abundance. Scheffe's test was used to determine significant differences between group means. A simple t-test was used to test for differences between recordings before and after exposure. Herring were excluded from analysis due to low numbers.			
Exposure Regime				
Source	# airguns:	2 x 20	shot interval:	25 m
	total volume:	2 x 3090 cui	source level:	222.6 dB_{p-p} @ 1m
Distance to Source	< 50 km			
Received Levels	Not measured. 197 dB at 20m, 189 dB at 50m assuming spherical spreading.			
Exposure Duration	12 days of active surveying spread over a month.			
Results				
Behavioural	No convincing evidence of short-term scaring effects on the horizontal scale. Blue whiting and mesopelagics were found in deeper waters during seismic exposure compared to periods without shooting (20 and 50 m deeper respectively), indicating vertical movement as a short-term reaction. Average density of fish was lower in seismic survey area, with increasing abundance at distance. Fish density appeared higher at about 37 km (20 nm) from center of survey area. This may be evidence of long-term effects or may be related to other factors.			
Conclusions of Report	This study emphasizes the importance of further studies on the effects of seismic noise on fish behaviour. However, future studies should be designed to distinguish between possible effects of a seismic source and other variables such as temperature, salinity, currents and food availability. While results are inconclusive, the present findings do support the use of management actions to restrict seismic surveying close to spawning grounds and over well-established migration routes to spawning grounds.			

Wardle, C.S., Carter, T.J., Urquhart, G.G., and Johnstone, A.D.F. 2001. Effects of seismic air guns on marine fish. *Cont. Shelf Res.* 21:1005-1027. [also reported in Wardle and Carter 1998]	
Study Information	
Study Type	Experimental
Purpose	To investigate the effects of an airgun on the behaviour of reef fish.
Species	Pollock (*Pollachius virens*)
Location	Firemore Bay in Loch Ewe, Scotland
Timing	Aug 19-23, 1998
Conditions	Isolated underwater reef rising ~7m; water depth of 10-20m.
Methodology	
Experimental Design	Fish were caught on and around Fish Rock with a barbless hook and line. Five fish were selected for tagging with an acoustic pinger. Each fish was measured, tagged, and then released at the capture site. The position of each fish was monitored using a fixed array of seven hydrophones separated by 100 m. Of the five fish that were tracked for a period of up to 18 days, only two remained close enough to provide useful results. An underwater video camera (equipped with floodlight) was also positioned on the sea bed at the north-east edge of Fish Rock and continuous recordings were made over a two-week period. An airgun was deployed after 9 days of observations and was fired intermittently over a period of 4 days. During firing of airgun, the camera was switched from time-lapse to real-time to monitor behaviour. A broadband hydrophone was positioned near the camera to record received sound levels. The airgun was fired at various distances (109, 90, 16 and 5.3 m) from the video camera.

Analysis	Positions of tagged pollock were superimposed on a map of the reef and calculations were made of distance from source over time. Video tapes were analysed to provide fish abundance and activity within the field of view. Observations of small, medium and large gadoids were grouped into 30 min bins, as were observations of "other fish", and an index of abundance for each bin was plotted over time. No statistical analysis of results is reported.			
Exposure Regime				
Source	# airguns:	3	shot interval:	variable
	total volume:	450 cui (2000 psi)	source level:	Not provided.
Distance to Source	> 5.3m			
Received Levels	195-218 dB at TV (218 dB at 5.3m, 210 dB at 16m and 195 dB at 109m).			
Exposure Duration	Airgun fired once per minute for 8 periods, ~300 shots over 4 days.			
Results				
Behavioural	Tagging : Two tagged pollock did not move away from reef and firing of airguns did not affect diurnal rhythm. Long-term day-to-night movements of 2 pollock were changed by exposure to airguns - one more than other. TV Observation : Fish showed c-start reaction to all shots (195-218 dB). When visible, fish fled from source. When not visible, fish would carry on with activity, often continuing toward source.			
Conclusions of Report	Airgun impulses generated in this study were sufficient to cause an alarm response in fish (C-start) but did not chase fish away or change their overall swimming behaviour. This response may have been influenced by the stationary nature of the sound source and the fact that it was not accompanied by other directional sound sources, such as vessel-generated noise. An airgun impulse on its own may not be sufficient to allow for a directional response of fish. It is also possible that this sound source was not of sufficient irritation to cause this resident population of fish to leave their reef.			
Related Papers	Wardle and Carter (1998)			

Weinhold, R.J. and Weaver, R.R. Unpublished, 1972. Seismic air guns affect on immature coho salmon. Preprint for the 42nd Annual Meeting of the Society of Exploration Geophysicists.				
Study Information				
Study Type	Experimental			
Purpose	To determine if the use of seismic air guns in shallow water was injurious to fish and to determine the lethal radius of this equipment.			
Species	Coho salmon (*Onchorhynchus kisutch*)			
Location	Lake Union, Washington.			
Timing	May			
Conditions	Lake depth of 13m.			
Methodology				
Experimental Design	Separate groups of ten coho each (total of 60 fish) were subjected to the firing of one 20 cui airgun at 1m, 5m, and 10m and a 240 cui airgun array at 1m, 5m and 10m. They were then observed for 72 hours. 20 coho were used as controls and exposed to similar conditions as test fish, except for exposure to seismic impulses.			
Analysis	Observations reported in table format.			
Exposure Regime				
Source	# airguns:	a) 1, b) 8	shot interval:	n/a
	total volume:	a) 20, b) 240 cui	source level:	a) 234 dB @ 1m b) 241 dB @ 1m
Distance to Source	1-10m			
Received Levels	a) 208 - 234 dB, b) 222 - 241 dB			

Exposure Duration	1 shot
Results	
Physical	One salmon died 60 hours after exposure (1m from 20 cui airgun); however, no external aberrations or internal hemorrhaging were observed. Subsequent reports make no mention of this fatality. One dislocated bit of tissue was found inside a swim bladder (10m from 20 cui airgun) -- judged to be unrelated to airgun exposure. Half of a left operculum was missing (1m from 240 cui array); this was judged to be an old injury as it did not appear to be of recent removal.
Conclusions of Report	Seismic air guns operated under these conditions appeared to exert no harmful effects on fish.

Appendix C – Summary of Studies using Non-Airgun Sources

Only portions of experiments related to adult and juvenile fish are summarized here. References are listed in alphabetical order by first author.

Dalen, J. and Knutsen, G.M. 1987. Scaring effects on fish and harmful effects on eggs, larvae and fry by offshore seismic explorations. Pp.93-102. In. Merklinger, H.M. (ed) Progress in underwater acoustics. Plenum Press: New York.	
Study Information	
Study Type	Experimental
Species	cod (*Gadus morhua*)
Location	North Sea
Timing	June 1984
Conditions	Water depths ranged from 100 – 300m.
Methodology	
Experimental Design	Eggs, larvae and fry of cod were placed in plastic bags and transferred to study area. Large fry were placed in 40 cm^3 net enclosure and lowered with sound source to 4 m from sea surface. The distance between sound source and fry was varied from 1 to 10m. Control fish were treated similarly except for exposure. Fry were dissected for morphological changes upon death or after 7 days. Only results for fry are reported here.
Exposure	
Source Type	Watergun (8610 cui)
Source Level	229 dB at 1m
Distance to Source	1 – 10m
Exposure Duration	Not reported.
Results	
Physical	Exposure to watergun resulted in 90% mortality at 2m, with evidence of ruptured swimbladders and hemorrhaging. 30% also had ruptured bellywalls. One fish died 2 days after exposed to the watergun at 6m. All fish exposed at this distance had troubles with balance.
Conclusions of Report	Waterguns can cause significant lethal impacts within 2m.
Related Papers	Dalen and Raknes (1985a, 1985b)

Enger, P.S. 1981. Frequency discrimination in teleosts --- central or peripheral? Pp. 243-253. *In* W.N. Tavolga, A.N. Popper and R.N. Fay [ed.]. Hearing and sound communication in fishes. Springer-Verlag, New York, NY.	
Study Information	
Study Type	Experimental
Species	Cod (*Gadus morhua*), ~25 cm (n=30)
Location	Laboratory
Timing	Not described
Conditions	Aluminum tube, 71 cm long with 12 cm inner diameter.
Methodology	
Experimental Design	Small cod were held in a mesh plastic cage in the middle of an aluminum tube. Two loudspeakers on either end of the tube were operated in phase. Exposure time was varied from 1 to 5 hours, at which point the fish were decapitated and the brain removed for analysis. Saccular sensory maculae were examined for damage using scanning electron microscopy. Control fish were also examined.

Exposure	
Source Type	Loudspeaker
Source Level	180 dB re 1 µPa (80 dB re 1 µbar)
Frequency	50, 100, 200, 300-400
Distance to Source	~35 cm
Exposure Duration	1 – 5 hours
Results	
Physical	Patches of sensory epithelium were destroyed, i.e. missing, in fish exposed to all frequencies tested. Areas lacking cilia were not detected in any of the control fish. There appeared to be a tendency for saccular maculae to be destroyed more anteriorly as the sound frequency increased. The central region of the saccular maculae was impacted by all frequencies. Higher frequencies (300-400 Hz) also impacted the anterior portion of the maculae while lower frequencies (50 Hz) impacted the posterior portion.
Conclusions of Report	Sensory maculae can be destroyed by excessive sound stimulation and the area affected will depend on the sound frequency.

Hastings, M.C., Popper, A.N., Finneran, J.J. and Lanford, P.J. 1996. Effects of low-frequency underwater sound on hair cells of the inner ear and lateral line of teleost fish *Astronotus ocellatus*. *J. Acoust. Soc. Am.* 99(3):1759-1766.	
Study Information	
Study Type	Experimental
Species	Oscar (*Astronotus ocellatus*)
Location	Ohio State University and University of Maryland at College Park
Conditions	Tank enclosure of 1.2 water depth.
Methodology	
Experimental Design	Fish were stimulated with sounds generated from a sound projector along a waveguide. After 1-4 days, fish were killed and tissue samples were fixed, shipped from Ohio to Maryland, processed, then evaluated using a scanning electron microscope. “Double-blind” procedures were followed. Five control fish were exposed to similar conditions except for sound exposure.
Exposure	
Source Type	Sound projector
Frequency	60, 300 Hz
Duty Cycle	Continuous wave, 20%
Magnitude	100, 140, 180 dB
Distance from Source	~3.8m
Exposure Duration	1 hr
Results	
Physical	4 of 5 fish exposed to 300 Hz at 180 dB continuous wave signal for 1 hr and allowed to survive for 4 days showed some (<15%) damage to the striola regions of the utricle and/or lagena of at least one ear. No damage was seen in the lateral line or saccule and cristae of the inner ear. Under other exposure conditions (60 Hz continuous wave, 300 Hz continuous wave at 100 or 140 dB, 300 Hz wave with 20% duty cycle), test fish results were generally similar to controls, except for a few cases (<10 epithelia) where damage to ciliary bundles covered an area similar to that of the tip of the forceps used to extract otoliths or was located close to major breaks in tissue.
Conclusions of Report	Exposure to 180 dB continuous wave signal at 300 Hz caused some limited hair cell damage to the inner ear of oscar. This damage was restricted to the striola region, which may be the area most sensitive to motion of otoliths during sound exposure or to there differences in structure from other hair cells.

Haymes, G.T. and Patrick, P.H. 1986. Exclusion of adult alewife *Alosa pseudoharengus,* using low frequency sound for application at water intakes. *Canadian Journal of Fisheries and Aquatic Sciences* 43: 855–862.	
Study Information	
Study Type	Experimental
Species	Alewife (*Alosa pseudoharengus*)
Location	Lake Ontario
Timing	July-Aug 1983, 1984
Conditions	78m offshore, 6m water depth
Methodology	
Experimental Design	An experimental structure 9m wide extending from surface to bottom was fitted with 1-12 pneumatic poppers. 3.8 cm mesh gillnet was used to capture alewife passing through the structure. Collection nets were placed on either side of the structure to verify presence of alewife in the area. In 1994, experimental trails involved firing of 12 poppers. In 1993, the number of poppers fired was varied (1, 2, 4, 6, 8 or 12). Control trails were run without poppers operating.
Analysis	An effectiveness index was calculated as the difference between catch during experimental conditions and catch during control conditions on the same night as a percentage of the control catch. Parametric statistics were used to evaluate results.
Exposure	
Source Type	1-12 pneumatic poppers
Frequency	20-1000 Hz, with most energy at 60 Hz
Duty Cycle	15 impulses per minute
Magnitude	12-21 MPa
Received Levels	Peak pressure at 32m was ~400 Pa (172 dB) for 1 popper and ~2300 Pa (187 dB) for 12 poppers.
Exposure Duration	3 x 2 hrs
Results	
Behavioural	Catches of alewife were significantly lower ($p<0.05$) when poppers were operating than during control tests. The effectiveness of excluding alewife from the experimental structure was 95-99% for a 12 popper array, 85-88% for 4 poppers and 71-77% for 1 popper. Effectiveness was not reduced over the 6 hours of testing. During trial of 8 poppers, sonar monitoring showed moving toward the structure, remaining in front of the structure, but moving 1-4m away when poppers fired. Authors concluded that these were probably not alewife.
Conclusions of Report	Low-frequency, high amplitude sound produced by pneumatic poppers can be effective at repelling alewife. The extent of influence of a single popper was estimated to be ~10m.

Popper, A.N. and N.L. Clarke. 1976. The auditory system of the goldfish (*Carassius auratus*): effects of intense acoustic stimulation. Comp. Biochem. Physiol. 53A: 11-18.	
Study Information	
Study Type	Experimental
Species	Goldfish (*Carassius auratus*)
Location	Not described
Timing	Not described
Conditions	Laboratory
Methodology	
Experimental Design	Auditory thresholds were determined using avoidance conditioning and threshold tracking or classical conditioning of respiratory suppression and method of limits. Each fish’s normal auditory threshold was determined on day

	1. On day 2, fish were placed in a small aquarium and exposed to pure-tone stimulation for 4 hours after which their auditory thresholds were immediately measured (n=4 for each test condition). On day 3, thresholds were measured again. If thresholds had not returned to day 1 levels, they were tested on successive days until recovery was achieved.
Analysis	
Exposure	
Source Type	Pure tones generated with an audio generator
Frequency	300, 500, 800, 1000 Hz
Source Level	132 – 152 dB re 1 µPa (32 – 52 dB re 1 µbar)
Received Levels	Within 4 dB of source levels
Exposure Duration	4 hours
Results	
Physical	Temporary threshold shifts were observed in goldfish exposed to pure tones at all frequencies and sound pressure levels tested; however, not all results were statistically significant. Using a test frequency of 500 Hz, exposure to 149 dB at 300, 500, 800 and 1000 Hz resulted in statistically significant threshold shifts, as did exposure to 146 and 152 dB at 500 Hz. Exposure to 137 and 143 dB at 500 Hz did not result in significant shifts. Using a test frequency of 800 Hz, exposure to a sound pressure level of 149 dB at 500, 800 and 1000 Hz resulted in statistically significant threshold shifts, but not at a frequency of 300 Hz. Exposure to 132, 137 and 146 dB at 800 Hz also resulted in statistically significant shifts, as did exposure to 152 dB at 500 Hz.
Conclusions of Report	The teleost inner ear responds in a complex manner to different stimulating frequencies and this may indicate some degree of spatial signal analysis in the inner ear.

Scholik, A.R. and H.Y. Yan. 2001. Effects of underwater noise on auditory sensitivity of a cyprinid fish. Hearing Res. 152: 17-24.	
Study Information	
Study Type	Experimental
Species	Fathead minnow (*Pimephales promelas*), 4.32 – 8.08 cm length
Location	University of Kentucky
Timing	Not described
Conditions	Laboratory conditions
Methodology	
Experimental Design	Fathead minnows were obtained from a local hatchery and maintained in filtered aquaria. Groups of fish (n<8) were exposed to various durations of white noise in a small tub with a water depth of 5.5 cm. To study effects of immediate exposure, fish were kept in isolated and quiet aquaria for up to 12 hours after exposure at which point their auditory thresholds were measured using the auditory brainstem response technique. To study recovery after exposure, groups of fish were held in aquaria for 1 – 14 days after exposure prior to measurements of their auditory thresholds. During this time, filters were operated for 30 min per day to minimize extraneous noise exposure.
Analysis	Results for each frequency were compared using an unpaired t-test (one tailed). Critical values were adjusted to account for multiple comparisons using the sequential Bonferroni technique (Rice, 1989). Separate one-way ANOVAs were then used to compare exposure duration effects and recovery duration effects at each frequency, where auditory thresholds of exposed fish were compared to controls using Dunnett tests (Bonferroni adjusted).
Exposure	
Source Type	White noise from a speaker hung 1m above the water surface

Frequency	0.3 – 4.0 kHz
Source Levels	142 dB
Exposure Duration	2, 4, 8 or 24 hours
Results	
Physical	After 1 hr of exposure to frequencies of 1, 1.5 and 2 kHz, hearing thresholds of goldfish were significantly elevated as compared to controls. After 2 hours of exposure, frequencies of 0.8, 1, 1.5 and 2 kHz resulted in significantly elevated hearing thresholds. Increases in thresholds obtained after 2 hours of exposure were similar to increases obtained after 4, 8 and 24 hours of exposure. After 24 hours of exposure, 5 out of the 8 frequencies tested (0.3, 0.8, 1.0, 1.5 and 2.0 kHz but not 2.5 or 4 kHz) resulted in a significant threshold increases. Recovery of auditory thresholds to pre-exposure levels was dependant on exposure duration and frequency. For exposure to 24 hours at 0.8 and 1 kHz, recovery occurred within a day. For exposure to 24 hours at 1.5 and 2 kHz, full recovery was not observed after 14 days. However, recovery from exposure to 2 hours at 1.5 and 2 kHz was seen after 6 days.
Conclusions of Report	The hearing of fathead minnows can be impacted by exposure to white noise. These effects can be long-term (> 14 days). Elevation of auditory thresholds after noise exposure was dependant on frequency and exposure duration.

Scholik, A.R. and H.Y. Yan. 2002. The effects of noise on the auditory sensitivity of the bluegill sunfish, *Lepomis macrochirus*. Comp. Biochem. Physiol. 133A: 43-52.	
Study Information	
Study Type	Experimental
Species	Bluegill sunfish (*Lepomis macrochirus*), 7.23 – 10.54 cm length
Location	University of Kentucky
Timing	Not described
Conditions	Laboratory conditions
Methodology	
Experimental Design	Bluegill sunfish were obtained from a local hatchery and maintained in a 1200L (320 gallon) tank with filtration system. Fish were exposed to sound in a small tub with a water depth of 5.5 cm. Groups of fish (n=6) were exposed to various durations of noise from 2 to 24 hours. Hearing thresholds were measured immediately after exposure using the auditory brainstem response technique. To investigate recovery, auditory thresholds were measured 1, 2, 4 and 6 days after exposure of other groups of fish (n=6) to white noise. Controls were used.
Analysis	Results were assessed using one-way analysis of variance (ANOVA) with exposure frequency (Hz) and days of recovery as factors.
Exposure	
Source Type	White noise from a speaker hung 1m above the water surface
Frequency	0.3 – 2.0 kHz
Source Levels	142 dB
Exposure Duration	2, 4, 8 or 24 hours
Results	
Physical	Exposure resulted in slight but not statistically significant increase in auditory threshold as compared to controls (P>0.05).
Conclusions of Report	The hearing of bluegill sunfish is minimally affected by exposure to intense sound. Differences in the auditory capabilities of fish should be taken into consideration when examining the potential impacts of intense noise exposure.
Related Studies	Scholik and Yan, 2001.

Smith, M.E., A.S. Kane and A.N. Popper. 2004a. Noise-induced stress response and hearing loss in goldfish (*Carassius auratus*) J. Exp. Biol. 207: 427- 435.	
Study Information	
Study Type	Experimental
Species	Goldfish (*Carassius auratus*)
Location	Aquatic Pathobiology Laboratory, University of Maryland
Timing	Not described
Conditions	Laboratory conditions
Methodology	
Experimental Design	Goldfish were obtained from a local hatchery and maintained under laboratory conditions. To study effects of long-term exposure on stress and hearing thresholds (a), 42 goldfish were maintained in 600L glass aquaria and groups of 5-6 fish were exposed to noise for durations of 1, 3, 7, 14 or 21 days. To study effects of short-term exposure on stress (b), groups of six goldfish were maintained in 76L aquaria and exposed to noise for durations of 0, 10 or 60 min. To study effects of short-term exposure on hearing (c), groups of six goldfish were exposed to noise in 19L bucket for durations of 0, 10, 60 min or 24 hours. Blood plasma cortisol and glucose concentrations were measured as an indication of primary and secondary stress response. Hearing thresholds were measured using auditory brainstem response.
Analysis	Results of studies on stress response were tested using analysis of covariance (ANCOVA), with exposure duration as a factor and bleeding order as a covariate. When significant main effects of exposure duration were found, Wilcoxon signed ranks were used to make pairwise comparisons. Results from hearing threshold studies were tested using analysis of variance (ANOVA) with exposure duration and frequency as factors. Tukay's post-hoc test was used to conduct pairwise comparisons of specific frequencies when significant main effects were found (Zar 1984). Regression analysis was used to investigate effects of exposure duration on temporary threshold shift.
Exposure	
Source Type	White noise from a minidisk player played through an underwater speaker
Frequency	0.1 kHz – 10 kHz
Received Levels	160-170 dB total sound pressure level
Exposure Duration	a) 1, 3, 7, 14 or 21 days b) 0, 10 or 60 min c) 0, 10, 60 min or 24 hours
Results	
Physical	Exposure to white noise resulted in significant but temporary increase in auditory threshold of goldfish for all frequencies tested. Auditory thresholds shifted by 5 dB after 10 min of exposure and 28 dB after 24 hours of exposure. There was no further shift in hearing evident after 7 or 21 days. Goldfish exposed to noise for 24 hours had improved hearing 1 day after exposure, though full recovery was not observed after 18 days. After long-term exposure, recovery to pre-exposure thresholds took ~14 days.
Behavioural	Goldfish exhibited an initial startle response at the onset of noise exposure, but this response lessened within a few minutes. No avoidance was observed.
Physiological	Noise exposure did not significantly affect cortisol or glucose concentrations in long-term noise experiments ($P<0.10$); neither did it significantly affect glucose levels in short-term stress experiments ($P=0.27$). Noise exposure, however, did significantly affect plasma cortisol levels in the short-term noise experiment ($P=0.01$). Relative to controls, mean cortisol levels tripled after 10min of noise exposure than decreased to control levels after 60min of noise exposure.

Conclusions of Report	Although behavioural response of fish to noise may be transient, damage to their ears may happen quickly and have a lasting effect. Temporary threshold shift in goldfish was observed after only 10 min of exposure, which may have reduced the perceived sound level and physiological stress.

Smith, M.E., A.S. Kane and A.N. Popper. 2004b. Acoustical stress and hearing sensitivity in fishes: does the linear threshold shift hypothesis hold water? J. Exp. Biol. 207: 3591-3602.	
Study Information	
Study Type	Experimental
Species	Goldfish (*Carassius auratus*) and tilapia (*Oreochromis niloticus*)
Location	Aquatic Pathobiology Laboratory, University of Maryland
Timing	Not described
Conditions	Laboratory conditions
Methodology	
Experimental Design	For short-term exposure experiments (a), goldfish were exposed to white noise in 19L buckets. For experiments on long-term exposure (b), goldfish and tilapia were maintained and exposed to noise in 600L glass aquaria. Hearing thresholds of experimental and control fish were measured on each specified day using auditory brainstem response.
Analysis	Results were tested using ANOVA with sound pressure level and frequency as factors. Tukay's post-hoc test was used to conduct pairwise comparisons between specific frequencies when significant effects were found (Zar 1984).
Exposure	
Source Type	Underwater speaker, white noise
Frequency	100 – 10,000 Hz
Source Levels	a) 130, 140, 160, 170 dB b) 164 – 170 dB
Received Levels	a) 166 – 170 dB b) 161 – 170 dB
Exposure Duration	a) 24 hours b) 7 days, 21-28 days
Results	
Physical	In the short-term noise experiments, there was a significant increase in the auditory threshold of goldfish (i.e. hearing loss) for each source level tested. At 130 dB, statistically significant increases in auditory threshold occurred for frequencies of 600-4000 Hz ($p<0.05$). At 140, 160 and 170 dB, significant increases occurred at all frequencies tested ($p<0.05$). In the long-term noise experiments, tilapia exposed to white noise for 7 days did not exhibit significant differences in auditory response from controls. After 28 days, some difference was detected but this was only significant at 800 Hz (thresholds were higher by 10 dB, $p=0.02$). Goldfish exposed for 7 days showed significant threshold shifts of up to 25 dB. Temporary threshold shifts occurred at all frequencies tested. Results after 21 days were not significantly different from results after 7 days.
Behavioural	Goldfish exhibited an initial startle response to the onset of noise, which diminished over a few minutes. Tilapia did not exhibit a startle response to the sound levels tested. No avoidance behaviour was observed.
Conclusions of Report	Tilapia exposed to continuous white noise for 28 days demonstrated little or no hearing loss, while goldfish exposed to white noise demonstrated considerable auditory threshold shift (25 dB) after only 24 hours of exposure.

Sverdrup, A., Kjellsby, E., Floysand, R., Knudsen, F.R., Enger, P.S., Serck-Hanssen, G. and Helle, K.B. 1994. Effects of experimental seismic shock of vasoactivity of arteries, integrity of the vascular endothelium and on primary stress hormones of the Atlantic salmon. *J. Fish Biol.* 45:973-995.	
Study Information	
Study Type	Experimental
Species	Atlantic salmon (*Salmo salar*)
Location	Bergen High Technology Centre
Conditions	9-10°C, running aerated water in a tank with a depth of 5m.
Methodology	
Experimental Design	Two sets of experiments were conducted, one focusing on blood vessel morphology and function (n=42) and one focusing on plasma and tissue samples (n=36). Two hours prior to experimentation, ~40 fish were transferred to a circular tank. Ten explosions were then discharged at 7-min intervals over a period of 70 min. within a net enclosure (1.5m^3) at the center of the tank. Pairs of test fish were killed at 0, 6, 12, 24, and 48 hours after exposure. Six control fish were sampled 2 hours prior to experimentation, and 2 control fish were sampled at 0, 6, 12, 24 and 48 hours after experimentation. Observations continued for 7 days. Controls were held in a separate, though identical tank. Studies of stress caused by transfer from one tank to another were conducted.
Exposure	
Source Type	Electrical percussion caps
Frequency	500-5000 Hz
Received Levels	~2 MPa (246 dB) at 1.3m from source
Exposure Duration	10 discharges over 70 min.
Results	
Physical	No mortality observed within 7 days after exposure. Blood vessels indicated physical damage (missing endothelial cells) and functional damage immediately upon exposure to intense sound and up to 12 hours afterwards. Endothelial cell morphology and vessel function appeared to be restored after 7 days.
Behavioural	Temporary cessation of swimming for a few minutes. No jumping, flight reaction or loss of orientation observed.
Physiological	Primary Stress Hormones: No immediate change in plasma cortisol upon exposure (0 hrs); declines observed after 6 (minimum levels) and 12 hours; return to pre-shock values after 24 hours; and continued increase to 48 hours ($p<0.05$). Plasma noradrenaline did not appear to increase upon exposure. Plasma adrenaline peaked after 6 hours ($p<0.05$) and was still significantly elevated after 12 hours, but not significantly elevated after 24. A significant decline in noradrenaline was observed over the 48 hour post exposure period. Secondary Stress Parameters: Significantly lower atrial contents of adrenaline were apparent after 24 and 48 hours. No significant changes in plasma chloride were observed.
Conclusions of Report	These experimental conditions (rise time of 40μs and frequencies of 500-5000 Hz) were more extreme than those produced by airguns (10-20 ms and 300-400 Hz) and yet no mortalities were observed within 7 days of exposure. However, salmon were clearly impacted to some degree. The behavioural response of "freezing" in place demonstrated here is different from the flight response observed in other studies. Damage to vascular endothelium was likely a result of the severe shear forces of high energy pressure waves, which appeared to result in an impaired ability to release primary stress hormones, to contract the coeliaco-mesenteric artery in response to high potassium, acetylcholine, and therefore to express an alarm response. Damage was repaired and function restored after 12 hours.

Swartz, A.L. and Greer, G.L. 1984. Response of Pacific Herring, *Clupea harengus pallasi*, to some underwater sounds. Can. J. Fish. Aquat. Sci. 41:1183-1192.	
Study Information	
Study Type	Experimental
Species	Pacific herring (*Clupea hanergus pallasi*)
Location	Pacific Biological Station, B.C., Canada
Conditions	Fish held in net enclosure ($3m^3$) with a water depth of 8m. Studies conducted during daylight hours. Ambient noise < 75 dB re 1 μPa.
Methodology	
Experimental Design	Nine groups of 500 herring were placed in a net enclosure ($3m^3$), left to acclimate over night, and then exposed to various recordings and sounds. Recordings were played through an underwater sound projector located just outside the enclosure at 1.65m depth. Four groups of herring was exposed to field recordings in the morning and electronically generated sounds in the evening, four groups had this order reversed, and one group was only exposed to electronic sounds. Observations were made throughout testing. Controls consisted of a 10 sec playback of a blank tape.
Exposure	
Source Type	a) Field recordings of fishing vessel and gear noise b) Electronically generated sounds
Frequency	a) 0 – 3000 Hz (major frequency bands) b) 200 – 1000 Hz
Received Levels	a) 105 – 112 dB at center of enclosure b) 75 – 116 dB
Exposure Duration	Variable
Results	
Behavioral	Responses to sound stimuli included avoidance (swimming to far side of enclosure), alarm (rapid movement) and startle (powerful flex of the body followed by 5-10 of fast swimming). Some sounds were met with no response. a) Avoidance was the main response to playback of fishing vessel recordings. Startle response was seen occasionally but alarm response was never observed. No response was observed upon exposure to sonar or echo sounder recordings. Habituation to some sounds (40-hp gillnet punt, stationary seiner) was observed. b) Strongest alarm reaction was to fixed amplitude of 102 dB, fixed frequency of 200 Hz and irregular pulses. In general, irregular pulses elicited more reaction than regular pulses or continuous tones.
Conclusions of Report	Pacific herring are capable of directional and selective responses to sounds. The magnitude, direction and rate of change of amplitude were important factors affecting response duration and intensity, as were spectral content and pulse frequency.

Turnpenny, A.W.H., Thatcher, K.P. and Nedwell, J.R. 1994. The effects on fish and other marine animals of high-level underwater sound. A report by Fawley Aquatic Research Laboratories Ltd. For the Defence Research Agency.	
Study Information	
Study Type	Experimental
Species	Brown trout (*Salmo trutta*) – vented swimbladder not connected to inner ear. European sea bass (*Dicentrarchus labrax*) – closed swimbladder. Sole (*Solea solea*) – no swimbladder. Whiting (*Merlangius merlangus*) – closed swimbladder, close association with inner ear.
Purpose	To investigate potential injury and behavioural effects associated with low-

	frequency pure tone burst.
Location	Fawley, UK
Timing	Not described
Conditions	Experimental conditions within a pool of 5m diameter and 1m depth.
Methodology	
Experimental Design	High Level Sound Exposure tests: The transducer was placed at the edge of the test pool. A circular flow was generated by submersible pump to aid fish alignment. Fish behaviour was monitored using a television camera fixed above the pool. Fish were introduced into the pool the day before experimentation. A trail consisted of fish counts by positions made every 30 sec. over a 90 sec "sound on" period followed by a 210 sec. "sound off" period. Six test and corresponding control sequences were run. Behavioural tests: Four sound projectors were arranged on four sides of a 40x40x100 cm frame, facing towards the center. A $30cm^3$ cage made of PVC mesh was placed at the center of this frame. Batches of fish were placed in this cage and exposed to a same series of sound signals. Observations were made with a submersible closed-circuit TV camera. Received sound levels were recorded for each frequency tested. Fifteen fish were used in each trial. Upon exposure, fish were examined for signs of external injury and loss of equilibrium before being transferred to a holding tank and observed for 24 hours. At this time, the fish were dissected and examined for external or internal haemorrhaging, rupture of swimbladder or gut, and eye damage. Controls were conducted for species that demonstrated response to sound.
Analysis	Inside a round enclosure, fish positions could not be normally distributed, so significance of differences between test and control results were calculated using a non-parameteris Kolmogorov-Smirnov test. Habituation was determined as follows: For each test-control pair, the difference in the average distance from the sound source was plotted against the number of exposures, a linear regression line was fitted to the points, and a negative slope with a non-zero x-coefficient was considered evidence of habituation. Significance of internal and external damage was evaluated using a Chi-squared test.
Exposure	
Source Type	Electro-magnetic transducer
Frequency	95, 200, 410, 790 and 1,580 Hz
Received Levels	130-180 dB re 1 µPa
Exposure Duration	
Results	
Physical	Brown trout: None of the trout died immediately after exposure the sound sources; however, significant mortalities were observed after the 24-hour retention period after exposure to signals at 95 and 410 Hz when the sound pressure level was above 170 dB. Mortalities were non significant when the sound pressure level was reduced to 160 dB. Common injuries included swimbladder rupture and damage to the eye. Some trout showed no signs of phsyical injury and mortality was thought to have occurred as a result of phsyiological stress. Bass: No bass died during the high-level sound exposure experiments, even after 24-hours. A small number of bass did suffer from swimbladder damage, which was statistically significant at 410 Hz. Sole: No signs of injury upon sound exposure for all frequencies tested at sound pressure levels of 155-177 dB. Whiting: 47% of whiting exposed to the 95 Hz signal died during the 24-hour holding period, but no significant mortalities or injuries were observed for fish exposed to higher frequencies. A small number of fish exposed to 200 Hz did exhibit ruptured swimbladders.
Behavioural	Brown trout: No significant response to any signals. Behavioural avoidance

	threshold for pure tones in the 95-1580 Hz range appears to be above exposure levels tested here (150 dB). Bass: Significant responses observed at 95, 200 and 1580 Hz. No habituation observed. Startle reaction observed at start-up for 410 and 790 Hz. Behavioural avoidance threshold for pure tones at 95 Hz appears is calculated to be as low as 128 dB. Sole: No reaction to high level exposure experiments and therefore no behavioural studies conducted. Reaction thresholds for startle and avoidance appear to be above exposure levels (152-177 dB). Whiting: A slight reaction was detected at 95, 200 and 410 Hz. Reaction was not sustained over time and therefore was considered statistically non-significant ($p<0.05$). No significant change in reaction pattern was observed with repeated exposure during habituation assessment.
Conclusions of Report	Behavioural sensitivity appears to be lowest in flatfishes, which have no swimbladder, and also in salmonids (brown trout), in which the swimbladder is present but somewhat remote from the inner ear. Gadoid fish (cod, whiting), which have a close association between swimbladder and inner ear, display a relatively high sensitivity to sound pressure. It is suggested that 150 dB re 1 μPa may be a reasonable lower threshold for sound induced injury, with potential behavioural effects extending below this level. It is recommended that all frequencies between 0-3000 Hz be considered potentially harmful to fish to account for the range in species sensitivities. It can not be assumed that fish will avoid injurious levels of sound.

Appendix D – Summary of Other Literature Reviews

The "Report Summaries" section only includes summaries of references that have not been previously described in Appendix B. The "Additional Analysis" section provides new information on, or analysis of, studies already described in Appendix B.

Davis, R.A. and Thomson, D.H. 1999. Review of Potential Effects of Seismic Exploration on Georges Bank. Prepared by LGL Ltd. Environmental Research Associates for Submission to the Georges Bank Review Panel, Halifax, NS. LGL Report No. TA 2308-1.	
Additional References	
Schwartz and Greer (1984)	Avoidance (formed compact schools and moved slowly away from source), alarm (school packed, fled at high speed, dove repeatedly and changed direction), and startle (flexed their bodies than swam at high speed for 5-10 sec without changing direction) responses noted in penned herring exposed to 105-111 dB played from a sound projector held just outside a $3.3m^2$ enclosure. Stronger reaction observed to lower frequencies. No reaction to 28 kHz echosounder or 165 kHz sonar.
Wright (1982)	Conclusion that there is little evidence of injury or mortality resulting from air gun operation is reported.
Conclusions	Impacts of seismic surveying on catchability of cod, haddock, pollock, mackerel, herring, tuna and swordfish on Georges Bank are likely to be minor and limited to small areas. Impacts on flatfish are likely to be negligible. Interference between seismic operations and fisheries would preclude simultaneous conduct of both activities within the same area.
Related Papers	Davis et al. (1998)

Gausland, I. Unpublished, 2003. Report for Norwegian Oil Industry Association (OLF): Seismic Surveys Impact on Fish and Fisheries.	
Additional References	
Jákupstovu et al. (2001)	Results of this study were summarized, including how statistical analysis of logbooks did not clearly demonstrate any effect of seismic surveying on catch rates, but since 75% of fishermen interviewed believed that they had observed an effect that it was reasonable to assume some effect had occurred. The suggestion that natural variation in catch rates is so large that any effect of seismic noise would be masked was also reported. However, it was also noted that seismic surveying on the Faroe Plateau did not appear to have any lasting impact on fisheries success.
Additional Analysis	
Engas et al. (1993)	Initially, this paper is described as a "very comprehensive and thorough study of the possible impact of seismic surveys on the behaviour of fish" (p. 33). The reduction in catches observed within the seismic survey area is not refuted. However, conclusions that catches were also reduced in the surrounding area (1-18 nm) were refuted by stating that the graphs provided do not demonstrate a change in catch rates that can be specifically attributed to seismic activity. Rather, the graphs demonstrate a decreasing trend in catch rates throughout the study period. No statistical support for this interpretation is provided. The author suggests that the scaring effect of fisheries may have had a greater impact on catch rates than seismic surveying.
Slotte et al. (1999)	Conclusion that large-scale distribution of both herring and blue whiting demonstrated lower abundance after periods of seismic surveying was refuted by stating that this study did not produce convincing, significant [statistical?] evidence, that data were not collected under strict experimental conditions, and that mapped fish distribution over a wide area was quite variable and difficult to interpret.

Conclusions	Gausland concludes that these studies have demonstrated negligible direct physical damage to fish as a result of airgun operations but that behavioural effects may occur within close proximity (2 km) of a seismic survey. It is suggested that behavioural responses are not likely to result in long-term impacts on fisheries catch rates or to the size of fish stocks.

Hastings, M.C. and Popper, A.N. 2005. Effects of Sound on Fish. A report for the California Department of Transportation.	
Additional References	
Popper et al. (in prep)	Exposure to three emissions of 108 seconds each from a low frequency active sonar transducer (160-325 Hz) produced up to 10 dB of temporary threshold shift in rainbow trout (Oncorhynchus mykiss). Received levels were ~193 dB (rms). Recovery was observed within 24-48 hours. No mortality observed within 4 days after exposure. No obvious damage to internal organs, including the ear.
Popper et al. (in prep)	Exposure to five emissions from a low frequency active sonar transducer (160-325 Hz) produced 10-15 dB of temporary threshold shift in northern pike (*Esox lucius*) and lake chub (*Couesius plumbeus*) but no threshold shift in broad whitefish (*Coregonus nasus*). Recovery was observed within 24 hours.

Knudsen, F.R. and Enger, P.S. Unpublished. Seismic Surveying: The Effects of Air Guns on Marine Organisms. A report by the Cooperating Marine Scientists for the Norwegian Oil Industry Association.	
Additional References	
Wright (1982)	Conclusion that there is little evidence of injury or mortality resulting from air gun operation is reported.
Greene (1985)	Results were reported from this pilot study, including a reduction in rockfish catches during seismic operations and the observation of inconsistent. behavioural responses to seismic noise in rockfish (such as dispersion and movement); however, it was noted that no definite conclusions were made.
Dalen and Raknes (1982)	Reported results include: flight reaction by herring (*Clupea harengus*) upon exposure to 180-186 dB re 1 μPa ~35-70m from an airgun, and 1 of 10 coho salmon (*Onchorhynchus kisutch*) exposed to 238 dB re 1 μPa within 1m of the airgun died. No mortality observed when fish were placed 5m from airgun.
Knutsen and Dalen (1985)	Reported results include: no effects of Bolt 600B and Bolt 1500B airguns on cod fry (*Gadus morhua*) within a range of 1m; upon exposure to a water canon at a range of 2m, 90% of the cod fry died immediately or within 3 hours; and at 6m, all had temporary balance problems but recovered later.
Additional Analysis	
Matishov (1989)	An error in analysis by Matishov is noted. Matishov incorrectly reports results of Dalen and Raknes (1982), stating that an airgun caused mortality of cod fry at 2m when in fact it was the watergun that caused mortality.
Conclusions	No injury or mortality has been demonstrated to any life-stage of fish at a range of greater than 5m. Airgun pulses may frighten fish and cause reduced catch rates. Airguns generate pulses which may be heard by fish at a range of several kilometers, though fish are not necessarily frightened by these sounds. Salmon have been shown to be frightened by sounds of frequency less than 20 Hz at intensities 30-40 dB above their hearing threshold. The pain threshold for fish is essentially unknown. Long-term (>1 hour) exposure to intense sound may destroy sensory cells, though short duration sounds may not. Balance problems may be an issue at lower levels, though relationship to sensory damage is unknown.

Popper, A.N. 2003. Effects of Anthropogenic Sounds on Fishes. Fisheries Research 28(10): 24-31.	
Additional References	
Myrberg (1980)	Noted for conclusion that masking may prevent fish from hearing biologically important sounds.
Tolimieri et al. (2002)	Reference with regards to how some larval fish may use the sounds generated at reefs to locate these reefs and how there may be larval preference for noisier reefs.
Popper and Clarke (1976)	Results that hearing sensitivity of goldfish (*Carassius auratus*) was reduced after exposure to loud sounds over 7 days, but tended to improve over time (two weeks) were reported.
Additional Analysis	Anthropogenic sounds may cause masking of biologically important sounds. If physiological impacts or effects on hearing occur, than fish may lose their ability to detect predators and prey, communicate or determine the structure of the acoustic environment. This would be expected to impact fish survival. Most studies on loss of hearing in fish have been conducted with pure tones and may not be applicable to seismic sources. It is as yet unclear whether fish are able to regenerate sensory hair cells after damage. Further studies are required to differentiate between sound levels that cause temporary or permanent hearing loss, and responses in various species of fish. Few studies conducted on the stress response of fish to noise. Effects on sensory cells within the lateral line, and other organ systems, have not been studied.
Conclusions	Existing studies indicate that fish may be impacted by increasing levels of anthropogenic sound.

Turnpenny, A.W.H. and Nedwell, J.R. 1994. The effects on marine fish, diving mammals and birds of underwater sound generated by seismic surveys. A report by Fawley Aquatic Research Laboratories Ltd. For the for United Kingdom Offshore Operators Association Ltd: London.	
Additional References	
Hastings (1990)	Results reported, including lethal threshold for fish of 229 dB and transient stunning of fish at 192-198 dB (150 and 400 Hz). Recovery of fish typically occurred within 30 min. Pathological effects on fish also described, including damage to fine structure of the inner ear of cod (*Gadus morhua*) and goldfish (*Carassius auratus*) upon exposure to periods of continuous pure tones. Reportedly, cod were exposed to frequencies of 50-400 Hz at 180 dB, while goldfish were exposed to 250-500 Hz at 182-204 dB over a period of hours. Damage to ciliary bundles was observed in both species. No damage was observed in goldfish exposed to 150 dB (100-2000 Hz) for several hours. Turnpenny and Nedwell note that given the use of pure tones, these results may not be readily applicable to impulsive seismic sources.
Turnpenny, Thatcher and Wood (unpublished)	Avoidance response from twaite shad (*Alosa fallax*) at 138 dB re 1 μPa (40 dB above ambient) using an amplified electronic sound projector with frequency of 100-500 Hz, bandwidth of 1 Hz, 100% direct current, within an experimental pool of 1m depth and 5m diameter.
Blaxter et al. (1981)	Startle reaction of herring (*Clupea harengus*) elicited at 137-142 dB re 1 μPa using an electromagnetic vibrator with 1 Hz bandwidth and single pulses of direct current.
Schwartz and Greer (1984)	Avoidance, alarm and startle responses from Pacific herring (*Clupea harengus pallasi*) at 102-111 dB (30 dB above ambient) using an amplified electronic sound projector with variable frequencies of 200-1000 Hz, 50-77% direct current, within a marine net pen 30mx10mx7.6m and water depth of 15m.
Thatcher and Irving (1992)	Avoidance response from bass (*Dicentrarchus labrax*) at 138 dB re 1 μPa using an amplified electronic sound projector with frequency of 100-500 Hz, bandwidth of 1 Hz, 100% direct current at a power station intake with water depth of 10m. Reduction in fish catch by 39%.

Turnpenny et al. (1993) - reference not provided	Avoidance response from bass (*Dicentrarchus labrax*) and Atlantic salmon (*Salmo salar*) at 108-138 dB re 1 μPa but no effect on eels (*Anguilla anguilla*) at 138 dB re 1 μPa using an amplified electronic sound projector with frequency of 100-500 Hz, bandwidth of 1 Hz, 100% direct current, within experimental pools of 1-2m depth and 5-15m diameter.
Turnpenny (unpubl)	Report of unpublished studies on whiting demonstrating that rupture of swimbladders via rapid reduction of hydrostatic pressure was not necessarily lethal; swimbladders were observed to heal and re-inflate within 7 days. It was noted that increased risk of mortality may stem from increased predation on disoriented or unbalanced fish.
Additional Analysis	
Falk and Lawrence (1973)	Assumed a source level of 230 dB and a 20logR transmission loss to estimate a lethal radius of ~226-234 dB re 1 μPa. Suggested that for a 248 dB airgun, that the potential lethal range might extend to 8m under worst case conditions.
Koshleva (1992)	Source level assumed to be 14.2 MPa with peak pressure in the range of 220-240 dB re 1 μPa-m. Received levels at 0.5m (resulting in physical damage but no mortality) were estimated to be ~226-246 dB re 1 μPa, and received levels at 1m (no evidence of damage) were estimated to be ~220-240 dB re 1 μPa.
Holliday et al. (1987)	Only results on eggs and larvae are reported. However, source level from the single airgun is listed as 248 dB re 1 μPa-m and received levels at 3m is calculated to be 238 dB re 1 μPa.
Matishov (1992)	Source level of experiments on adult cod and plaice is assumed to be ~226 dB re 1 μPa-m (considered a typical output). From this, the received level at 4m (resulting in blindness) is estimated to be ~214 dB re 1 μPa and the received level at 2m (resulting in transient stunning and mortality after 48 hours) is estimated to be ~220 dB re 1 μPa.
Lokkeberg (1991)	Received levels at 5 km (rather than 5nm as described in the report) are estimated to be >161 dB re 1 μPa.
Lokkeberg and Soldal (1993)	Source level estimated to be ~239-250 dB re 1 μPa-m based on chamber volume reported. Received levels were estimated to be ~160-171 dB re 1 μPa.
Engas et al. (1993)	Reliability of received level estimates at 33 km (160 dB re 1 μPa) is questioned. In general, the quality of this experiment is applauded. For example, it is noted that experimental variables beyond presence of seismic survey activity, such as boat noise and biological sampling, were investigated for their ability to explain experiment results. However, the failure to record long-range sound levels and the limited duration of the study is noted. Discrepancy of these results as compared to results of other studies is attributed either to the larger fish size (small fish less may have higher tolerance than large fish) or to the possibility that diving reduces swimbladder volume, increases resonant frequency and hence the tolerance threshold.
Chapman and Hawkins (1969)	Source level described as 220 dB re 1 μPa-m, and received level at 54m estimated to be ~188 dB re 1 μPa.
Pickett et al. (1994)	Sound level of elicit effect in bass listed as 163-191 dB re 1 μPa (calculated, not observed). This level may be too high if transmission loss > 20logR.
Data Gaps	Persistence of effects has not been clearly established, though appear to be short-lived (<= duration of exposure) for the most part. Lack of direct measurements of received levels. Limited studies in shallow water. No studies to date on flatfish species (no swimbladders).
Conclusions	A very low risk of injury to any life-history stage of fish under normal airgun operating conditions is expected. Behavioural effects appear to include avoidance and reduced feeding activity. Gadid species appear more sensitive to noise than other species. Demersal species appear to descend in the water column as an initial response to noise, which may then be followed by horizontal dispersion. Pelagic species appear to respond to noise with

	horizontal dispersion. Fish size may influence response to sound, either as a result of swimming speed or sensitivity (resonant frequency of swimbladder). Sound propagation in shallow water will tend to be more complex and therefore more difficult to predict than in water >50m. However, transmission losses will tend to be higher in shallow water than in deep water, and thus the area of impact will tend to be reduced. A summary of generic predicted effects levels is provided: Effect — dB re 1 μPa Behavioural effects — 160-200 dB Transient stunning — 192 dB Internal injuries — 220 dB Fish mortality — 230-240 dB Avoidance thresholds can be achieved at lower levels (100-140 dB) using targeted frequencies and duty cycles of 50-100% (compared to ~33% for seismic airguns).

Turnpenny, A.W.H., Thatcher, K.P. and Nedwell, J.R. 1994. The effects on fish and other marine animals of high-level underwater sound. A report by Fawley Aquatic Research Laboratories Ltd. For the Defence Research Agency.	
Additional References	
Yelverton et al. (1975)	Conclusion that lethality of sound pressure to swimbladder fish is directly proportional to body weight is reported.
Larson (1985)	Conclusion that mortality of the most sensitive adult organisms may occur when peak pressure >= 229 dB re 1 μPa and rise time and decay time <= 1 ms is reported.
Hastings (1990)	Results similar to those reported in Turnpenny and Nedwell (1994); however, mortalities due to internal haemorrhaging after exposure to 192-198 dB re 1 μPa (gouramis, Belontiidae, 50-56% mortality) and 204 dB re 1 μPa (goldfish, *Carassius auratus*, 25% mortality) for 0.5-2 hours are also described.
Dalen (1973) - reference not provided	Sound level to elicit effect in herring listed as 180-186 dB re 1 μPa.
Matousek et al. (1988)	Sound level to elicit effect in alewife listed as 181 dB re 1 μPa. Source was a single airgun with source level 205 dB, primary frequency of 60 Hz, and bandwidth of 50-70 Hz. Studies conducted at a power station water intake at 2-6m depth.
Conclusions	Fish avoidance may occur in shallow water provided that the sound level received by fish is greater than the behavioural effects threshold.