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Effects of seismic and marine noise on invertebrates: A literature Review

Effets des bruits d'origine sismique et marins sur les invertébrés : une revue de littératures

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Abstract

The study on the effect of marine noises on invertebrate species is extremely limited. We have found 35 articles dealing with the possible effects of marine noise on invertebrates. Most of these are secondary or gray publications produced as internal industry reports, governmental technical reports, and other non-journal sources. Two sources of noise have been studied. The first, refractive seismographic surveys by explosives were examined in 15 articles. Nine of these described quantitative tests, two consisted of article reviews and two consisted of anecdotal information. However, seismographic surveys using explosives are an outdated method and do not add additional information to this study. The second source of noise, seismic surveys using air-guns were examined in 20 articles. The results of nine quantitative studies based on the summary by species and by sampling type showed five cases of immediate (lethal or physical) impacts and four cases of no impacts. One showed a case of physiological impacts and one article showed no physiological impact. Three cases showed behavioral impacts and one article showed no impact on behavior.

Through the current literature review, we recognized a total lack of the scientific documents on the possible impacts of seismic noise on marine invertebrates. In addition, among the literature cited in this document, a very limited number of experiments were scientifically and reasonably conducted. Squid (McCauley et al., 2000a) and crab behavior (Christian et al., 2003) have been studied by direct observations. Pre- and post seismic air-guns comparisons of catch rates were made by La Bella et al. (1996) and Christian et al. (2003) on various invertebrate species. The quantitative and anecdotal aspects of all other studies were inadequate for assessing the effects of explosives and seismic air-guns on invertebrates. In addition, in-depth analyses on physiological changes in animals exposed to seismic air-guns are quasi-absent.

The articles dealing with seismic effects on marine invertebrates are often difficult to obtain because they are mostly gray literature. As a result, many authors use report summaries rather than examining the original work. This has lead to misunderstandings and misinterpretation of the results of previous work. We found that it was often concluded that invertebrates are robust to noise from explosions and air-guns without support from empirical evidence.

Under the current knowledge on this subject, there is no robust scientific evidence to draw any conclusion (positive or negative effects). Any speculative description and opinion of the effects should not to be made and all concerned documents have to be thoroughly examined to properly cite the results of previous studies in order to avoid any misunderstandings or misconceptions. Marine invertebrates are important members of the marine habitat, food web and ecosystem. Comprehensive research programs should be instituted to thoroughly investigate the possible effects of the seismic activity on various marine invertebrates in order to buildup the scientific knowledge on this subject.

Résumé

Les effets sur les invertébrés des bruits produits en mer n’ont presque pas été étudiés. Nous n’avons localisé que 35 articles portant sur le sujet, dont la plupart sont des publications spécialisées secondaires ou prenant la forme de rapports internes de l’industrie, de rapports techniques gouvernementaux et de documents autres que ceux publiés dans les journaux. Deux sources de bruits ont été étudiées. La première, les relevés de sismographie-réfraction faisant appel à des explosifs, est l’objet de 15 articles. Neuf de ceux-ci décrivent des essais quantitatifs, deux sont des revues d’article et deux présentent de l’information anecdotique. Les relevés sismographiques aux explosifs sont cependant considérés comme une méthode désuète; les données ainsi recueillies ne sont donc pas très utiles pour la présente étude. La deuxième source de bruits, les relevés sismiques qui font appel à des canons à air, est l’objet de 20 articles. Les résultats de neuf études quantitatives reposant sur les résumés par espèce et par type d’échantillonnage révèlent cinq cas d’impacts immédiats (létaux ou physiques) et quatre cas d’impacts nuls. Une étude fait état d’impacts physiologiques et une autre, de l’absence de ceux-ci. Trois études ont démontré des impacts comportementaux, alors qu'une autre n'en signale aucun.

À la suite de la revue des documents scientifiques disponibles, nous avons constaté qu’aucun n’abordait les impacts possibles du bruit sismique sur les invertébrés marins. En outre, parmi les ouvrages cités dans le présent document, un nombre très limité d’expériences ont été réalisées de façon scientifique et raisonnable. Le comportement des calmars (McCauley et al., 2000a) et des crabes (Christian et al., 2003) a été étudié par observations directes. La Bella et al. (1996) et Christian et al. (2003) ont comparé les taux de capture de divers invertébrés avant et après des relevés sismiques avec des canons à air. Les aspects quantitatifs et anecdotiques de toutes les autres études étaient inadéquats pour ce qui est d’évaluer les effets des explosifs et du bruit sismique produit par les canons à air sur les invertébrés. En outre, les analyses détaillées des changements physiologiques produits chez les animaux exposés aux tirs des canons à air sont quasi inexistantes.

Il est souvent difficile d’obtenir les articles portant sur les effets de la prospection sismique sur les invertébrés marins parce que ce sont surtout des ouvrages à distribution interne. Il en résulte que de nombreux auteurs utilisent les résumés plutôt que les travaux originaux, ce qui mène à une mauvaise interprétation des résultats des travaux antérieurs. Nous avons constaté que des chercheurs concluent souvent, sans preuves empiriques, que les invertébrés tolèrent bien le bruit produit par des explosions et des canons à air.

À la lumière des connaissances disponibles sur le sujet, nous ne disposons d’aucune preuve scientifique solide nous permettant de tirer quelque conclusion que ce soit (effets négatifs ou positifs). Aucune description ou opinion conjecturale sur les effets possibles des bruits produits en mer ne devrait être faite et tous les documents pertinents doivent être minutieusement étudiés afin d’être en mesure de citer convenablement les résultats d’études antérieures pour éviter toute confusion ou méprise. Les invertébrés marins sont des membres importants de l’habitat, de la chaîne alimentaire et de l’écosystème marins. Des programmes de recherche intégrés devraient être mis sur pied en vue d’étudier à fond les effets possibles des activités sismiques sur divers invertébrés marins de sorte à accroître les connaissances scientifiques sur le sujet.

1. Introduction

Current knowledge on the impact of marine noises on invertebrate species is extremely limited. Most available information on explosive and air-gun effects on invertebrates comes from seismic surveys for oil and gas prospecting. In the past three decades, there are two dominating seismic sources. The first, are explosives such as dynamite, TNT and black powders, and were used before mid 1980's. The second, are air-guns producing sound levels of around 241-265 dB re 1µPa-m (Richardson et al., 1996) and have been used since the mid-1980's (Holliday et al., 1987). The pressure waves produced by air-guns used in modern seismic surveys seem to be substantially less harmful than those from explosives (Collins et al., 2002). Because of this difference in effect and because explosives are no longer used, results of these two seismic sources are tabulated separately by putting more emphasis on the seismic air-gun surveys in this document.

Very little is known about sound detection in invertebrates, however, many species have mechanosensors that have some resemblance to vertebrate ears (Popper, 2003). Horridge (1966) found underwater vibration receptors in many invertebrates e.g., fingers of a Mediterranean ctenophore (*Leucothea multicornis*), tentacles of the common ctenophore (*Pleurobrachia pileus*), the margin of a medusa (*Eutonia indicans*), hair-fun organs of the common lobster (*Homarus vulgaris*), and setae of non-motile cilia of the arrow-worms (*Spadellaa cephaloptera*). Frings and Frings (1966) showed reaction pattern of marine invertebrates induced by sound and related stimuli and the existence of potential phonoreceptors of various marine invertebrates.

In crustacean species, it is known that the main vibration receptors are in the statocysts and in the walking legs (Aicher et al., 1983), either in the cuticle (Shelton and Laverack, 1968; Barth, 1980; 1981) or in the joints between leg segments (Burke, 1954; Horch, 1971, 1974; Salmon and Horch, 1972). Tautz and Sandeman (1980) showed that crayfish (*Cherax destructor*) sensory hairs on their chelae are maximally sensitive to water vibration frequencies between 150-300 Hz. The amplitude threshold is about 0.2 µm water molecule oscillation. Tautz et al. (1981) showed two types of sensory hairs (smooth hairs and feathered hairs) on the second antenna in crayfish (*Astacus leptodactylus*). The lowest sound threshold occurred at 40 Hz for smooth hairs and 90 Hz for feathered hairs. The authors suggested that the flagellum-feathered hair system may permit the crayfish to detect and possibly locate moving objects in its immediate environment. Franzen (1995) showed that tellinid bivalves (*Macoma balthica*) are sensitive to frequencies in the minimum range of 50-200 Hz, which corresponds to shear-wave vibrations that propagate along the sediment surface. Heinisch and Wiese (1987) reported that the sensitivity to vibration of water and sand of the buried North Sea shrimp (*Crangon crangon*) itself is maximal at 170 Hz. A fixed behavior consisting of a fast backward flicking of the large second antennae was elicited at this frequency, with absolutely lowest threshold of acceleration of 81 cm/s^2, corresponding to the smallest particle displacement values of 0.7 µm. Tautz and Sandeman (1980) found the minimum threshold for just audible summed action potential of the mechanosensory nerves of claws of *Cherax* was 170 Hz corresponding to smallest particle displacement values of 0.2 µm (pda). Aicher et al. (1983) reported that the fiddler crab (*Uca pugilator*) will drum when a female approaches a signaling male or when visual signals are ineffective. Typically, in such a case, pulses of 300-500 ms duration are repeated at a rate of about 10-20/s. Near the animal, the energy spectrum of a single substrate-borne signal extends from 5 to 1500 Hz, with a broad maximum between 200 and 700 Hz (Salmon and Horch, 1972).

Shabalin (1991) observed the behavior of squid schools (*Todarodes pacificus*) using broad band acoustic stimulation at 0.4-10kHz (the acoustic pressure varied from 1 to 60 Pa and the ship noise was about 1Pa). The author concluded that the effects of acoustic stimulating on the squid bites are due to both squid reactions directly to the stimulus and also from fish responses to the stimulus. The author concluded that the fishing efficiency of squid can be improved by controlling artificial and bio-stimulus.

Lagardère and Regnault (1980), Lagardère and Spérandio (1981), Regnault (1981), Lagardère (1982), and Regnault and Lagardère (1983) showed that in aquarium under permanently high noise levels of around 30dB in the 25 to 400 Hz-frequency range, the growth and reproduction rates of sand shrimp (*Crangon crangon*) was significantly reduced. In addition, increased aggression (cannibalism), mortality rate and decreased food uptake were observed, but not quantified. This appeared to be symptoms of stress. The level of ammonia excretion and oxygen consumption rates increased at sound levels around 30dB. Alternatively, when the acoustic pressure of the environment was increased abruptly, the excretion rate increased but oxygen consumption decreased. These responses to abrupt changes usually disppeared within 3 hours. However, the metabolic response to a high ambient noise level was fully expressed within a few hours and there was no evidence of any adaptive reduction of metabolic rates over a period of observations (5 days).

Based on the published information, it is reasonable to conclude that marine invertebrates are sensitive to sounds and related stimuli and that a variety of behavioral responses may be induced by these stimuli. Invertebrates often have a limited mobility, and may not be able to readily migrate out of survey areas (Anonymous, 2003). The results of the effects of marine noises on invertebrates are namely published in gray literature (project reports, contract reports, conference proceedings etc…) as complementary observations to the main studied species, e.g. fish and mammals. Furthermore, testing protocols have not directly considered invertebrates. For this reason, it is difficult to compare results being obtained from different testing conditions and materials. There is a general belief that fish with air bladders are more susceptible to injury from underwater explosions than bladderless fish and invertebrates. Rulifson and Schoning (1963), and Anonymous (2003) for the effects of seismic air-guns hypothesized that it is possible that seismographic and seismic surveys may not cause mortality in the benthic species, based on their morphological structure and the absence of air bladders.

2. Literature Review

In order to find documents dealing with the possible effects of marine noises on invertebrates, we made computer and manual literature searches. A series of keywords pertinent to the subject (seismic, dynamite, TNT, explosives, marine noise, invertebrates, shrimp, crab, lobster, crustaceans, oyster, clam, squid, octopus, mollusks, benthic community) were used for searching in the electronic bibliography search systems (Waves, Cambridge Scientific Abstract and Current Contents) at DFO Gulf Region library. Gray literature search was also done by DFO COOGER office (Bedford Institute of Oceanography, Dartmouth, Nova Scotia).

Only portions of experiments relative to marine invertebrates are summarized in this document. Information relative to invertebrate larvae and plankton are cited elsewhere (see Payne et al.). Anecdotal information has been noted in the document but not tabulated. Publications dealing with the effects of explosives on invertebrates for the purposes other than seismic and seismographic surveys on invertebrates, e.g. the removal of navigational or natural hazards (Tollefson and Marriage, 1949; Thomson, 1958; Brown and Smith, 1972), effect of explosives or weapons (Knight, 1907; Gaspin, 1975; Gaspin et al., 1976) and dynamite fishing (e.g. Guard and Masaiganah, 1997) are not included in this document.

2.1 Summary by sound source

2.1.1. Effect of shock waves (refractive seismographic survey with explosives)

Rulifson and Schoning (1963) classified explosives by its property as follows; low explosive (e.g., black powder) which burns progressively for a relatively long period of time produce a comparatively slow buildup in pressure of the expanding gases with detonation speed at 2000 feet/second. This was used for seismographic surveying in California and Alaska but discontinued because of the hazard and the poor performance. High explosives, (e.g., dynamite, TNT) which burns almost instantaneously and produce a very fast build-up in pressure of the gases formed by the explosion with detonation speed ranging from 4000 to 23000 feet/second (TNT has a velocity of ca. 20000 feet/second). Blasting agent (e.g., NCN) alone is not explosive, but can be made to detonate by use of a high explosive primer. The velocity of their detonation waves ranges from 8000 to 16000 feet/second (mid range of dynamite) and are safe to handle. For this reason, blasting agent was used almost exclusively for seismic work during the later era of seismographic surveys using explosives.

Rulifson and Schoning (1963), and Keevin and Hempen (1997) provided a comprehensive review of the literature dealing with the effects of explosive on marine invertebrates including seismographic surveys and other use of explosive. However, a comparative review of the available results is impossible because the sound source level has rarely been reported. An exception, which was not associated with a seismic survey, described the effects of explosive trials on marine animals including invertebrates (Gaspin et al., 1976).

2.1.1.1 Immediate effects (immediate reaction, damage and mortality)

The effects of dynamite, used in refractive seismic exploration, on shrimp (*Penaeus setiferus*) and oysters (*Crassostrea virginica*), was first studied by Gowanloch and McDougall (1944). Charges of 200 and 800 pounds of 60% gelatin dynamite, unconfined and placed on the ocean floor in 18 feet of water, did not harm shrimp at a distance greater than 50 feet from the explosive. In addition, no mortality of oysters could be attributed to the explosion or its side effects (e.g. silt, gases etc.). The authors concluded that further studies are needed to check the validity of the conclusions. Another study was conducted by the same authors (Gowanloch and McDougall, 1945) by using 200-pound and 800-pound charges of 60% gelatin dynamite to examine the impact on oysters (*Crassostrea virginica*), shrimp (*Penaeus setiferus*), and crab (*Callinectes sapidus*) at the distances from the shot point varying between 50 and 400 feet. Shrimp were uninjured at 50 feet by the heavier shots and no conclusive mortality was observed for oyster. Later papers by Gowanloch (1946, 1948), added no new findings to these two initial experiments. (Tables 1, 17).

Aplin (1947) examined the effects of 20 pound charges of 60% Petrogel exploded 4 feet under the surface on invertebrates placed on the bottom at 55 feet in water depth. Spiny lobsters (*Panulirus interruptus*) placed on the bottom at the distance of 50 feet from the center of explosion, suspended in the depth of 4 feet under the surface and 50 feet from the center of explosion, and on the bottom at 51 feet under the explosion were found to be very resistant and suffered no immediate ill effects. Dissection of spiny lobster after being exposed to the explosion revealed no signs of inner damage. However, all abalones (*Haliotis corrugata and H. fulgens*) placed at 50 feet from the explosion point were dead within several hours after the explosion when placed at 51 feet under the explosion point. (Tables 2, 17).

Anonymous (1948) showed approximately 2% of immediate mortality of oysters exposed in bags on the bottom within 100 feet from a 30-pound, and 200 feet from a 300-pound suspended charge of TNT. Over a limited area, a relatively small percentage of the exposed oysters were killed by the underwater explosion. An experiment on blue crab (*Callinectes sapidus*) showed that lethal damage is limited to a radius of approximately 150 feet or less (Tables 3, 17).

Sieling (1951, 1953) examined oysters placed 20 to 250 feet from 20 to 50-pounds Nitramon charges. These charges were placed 30 feet and 70 feet under the ocean bottom, respectively. The results showed no adverse effects as close as 20 feet from the shot up to a period of four to eight months. His experiment also included glycogen analyses in the oyster tissue and is the only experiment that has observed physiological effects on exposed animals during the seismographic surveys using explosives (Tables 4, 17).

Kemp (1956) evaluated the effects of seismographic explosions (40-pound Nitramon) on shrimp (authors' note: species name was not given but *Penaeus* sp. according to Keevin and Hempen, 1997), oysters (*Crassostrea virginica*) and blue crabs (*Callinectes sapidus*). He concluded that shrimp and crabs were "*found to be completely immune to underwater explosions, since they suffered no ill effect whatsoever during the test*" (Tables 5, 17).

The Fish Commission of the State of Oregon (Anonymous, 1962) examined Dungeness crab (*Cancer magister*) mortality and damage caused by seismographic explosions (nitrocarbonate). Four treatment groups were examined : (1) shot versus control groups (immediate and after 96 hours sample retrieval), (2) 8, 15 and 35-fathoms, (3) surface (2-4 feet) versus submerged (20-40 feet) shots, and (4) 5-pound versus 25-pound charges. No significant difference among the four treatment groups was found. (Tables 6, 17).

Linton et al. (1985) studied the mortality in white shrimps (*Penaeus setiferus*), blue crabs (*Callinectes sapidus*) and American oysters (*Crassostrea virginica*) held in cages and exposed to a 33-meter strand of 100 gram/ 33 centimeter Primacord detonation. After 24 hours, white shrimp mortality was 10-35%, blue crab mortaility was 10-60% and oyster mortality was 5-15%. Specific mortality rates depended on the distance from the detonation center (Tables 7, 17).

Some anecdotal information, often post-explosions within a certain radius of the detonation is available. Kearns and Boyd (1964) reported the presence of a live crab* observed during post-detonation diving in an area 75 feet from a 25 pound explosion point at a depth of 32 feet. Fry and Cox (1953) observed during post-explosion diving that "*clams and tube worms were found, none of which had suffered ill effects from the blast*". They concluded that "*None of the invertebrates seemed to be affected; the sea anemones were extended, as were the tube worms; none of the corals had been broken; the sea urchins were still on the rocks and the sea cucumbers had not contracted*". (*Authors' note: possibly Dungeness crab, *Cancer magister*).

2.1.1.2 Behavioral changes

No study was found on the behavioral changes of invertebrate species caused by explosives used for refractive seismographic surveys.

2.1.1.3 Morphological, biochemical and physiological changes

Only Sieling (1951) examined glycogen levels in the tissues of the American oyster exposed to explosives. He concluded that "*Glycogen analyses did not show any consistent trend which would indicate that nutrition, or storage of reserve food in the tissues of oysters, was disturbed by the explosions or by the after-effects of seismographic operations*". Aplin (1947) mentioned that he examined spiny lobsters killed by seismographic explosives without any details. The authors provided a short description on the anatomical aspect of dead spiny lobster, i.e. *"(lobsters) when killed their viscera showed no signs of damage*".

2.1.2 Effects of seismic air-guns.

2.1.2.1 Immediate effects (immediate reaction, damage and mortality)

To assess immediate reaction, damage and mortality of the animals that directly received air-gun noise, direct observations were generally made in shallow water. In rare cases (e.g., McCauley et al., 2000a; Wardle et al., 2001; Christian et al., 2003), direct observations were made by means of underwater video camera.

Norris and Møhl (1983) cited unpublished work by Møhl et al.* that *Alloteuthis sublata* (mantle length of 4 cm) had a short term tolerance to sound level of up to 260 dB re 1μPa based on 17 trials, and lethal effects within 3-11 minutes after being exposed to sound levels at 246-252 dB re 1μPa for *Loligo vulgaris* (mantle length 18-27 cm) based on 5 trials (Tables 8, 18, 19). *Authors's note: B. Møhl, K.S. Norris, P. Norris and K.J. Staehr, M.S. (complete reference was not given).

Kosheleva (1992) tested a single air-gun of 60-180 in^3 with source levels of 220-240 dB re 1μPa on mollusks (mussels, *Mytilus edulis*), gastropods (periwinkles, *Littorina obstusata* and *L. littorea*) and crustaceans (amphipods, *Gammarus locusta*) at distances of 0.5 m or greater from a source level of 223 dB re 1μPa. Only the tests on mollusks and amphipods were successful (Dalen, 1994) and they found no discernible effects on amphipods and mollusks (Tables 9, 18, 19). (Authors' note: Based on the combined information from Kosheleva's conference abstract, Dalen (1994) who described species latin names, and Turnpenny and Nedwell (1994) who estimated the sound source levels).

Matishov (1992) described that the shell of one of three mollusks (Iceland scallop, *Chlamis islandicus*) split and 15% of the spines in seaurchins fell off when being exposed to a seismic air-gun (source level of 233 dB re 1μ Pa*) at a distance of 2 meters from the gun (Tables 10, 18, 19). *Authors' note: sound source level estimated by Anonymous (2002b).

Webb and Kempf (1998) exposed brown shrimp (*Crangon crangon*) in the Wadden Sea to an array of 15 guns with a total volume of 480 in^3 and a source level of 190 dB re 1μPa at 1 m at a depth about 2 m*. They found no mortality of shrimp and no evidence of reduced catch rate. They attributed the lack of an effect to the absence of gas-filled organs and a rigid exoskeleton (Tables 11, 18, 19). (*Authors' note: sound level, air-gun type and water depth are not cleary described)

Caged squid (*Sepioteuthis australis*) subjected to an individual operating air-gun showed behavioral changes and avoidance (McCauley et al., 2000a). They found an alarm response at 156-161 dB re1μPa rms, and a strong startle response at 174 dB re 1μPa rms involving ink ejection and rapid swimming. The caged squids also moved to the sound shadowed area of the cage. The authors suggested thresholds for affecting squid's behavior are at 161-166 dB re 1μPa rms (Tables 12, 18, 19).

Christian et al. (2003) did not detect any effects on the behavior of snow crab (*Chionoecetes opilio*) placed in cages and put on the ocean bottom at a depth of 50 meters after being exposed to sound levels of 197-237 dB from an air-gun array (Tables 13, 18, 19).

Guerra et al. (2004) reported two incidents of multiple standings affecting nine specimens of giant squids *Architeuthis dux* in 2001 and 2003 appeared to be linked spatially and temporally to geophysical prospecting using air-gun arrays in the Bay of Biscay. They showed evidences of acute tissue damage in the standed and surface-floting giant squids (Tables 14, 18, 19).

Anecdotal information:

Based on the underwater video camera observations on the behavioral reaction of fish vis-à-vis seismic noise, invertebrates* (crustaceans, echinoderms and mollusks) showed no signs of moving away from a reef when exposed to a sound pressure peak at between 195 dB and 218 dB re 1μPa) produced by a seismic triple G air-gun (Wardle et al., 2001). (*Authors' note: species name were not mentioned)

Anonymous (1999) described the THUMS Long Beach Company's 3-D seismic survey as follows " *In January, 1995, the THUMS Long Beach Company conducted a 3-D seismic survey in the Long Beach Harbor and vicinity with a large airgun array (a 12-gun, 1500 in^3 array was proposed in the environmental analysis). The environmental analysis concluded that the project was unlikely to have significant effects on fish or invertebrate populations in the harbour area and long-term effects on fish populations would be unlikely."*

Payne, J. F. and J. Christian (unpublished information) observed no immediate mortality within 48 hours in shrimp (*Pandalus borealis*), lobster (*Homarus americanus*) and scallops (*Placopecten magellanicus*), after being exposed at close range (- 1m) to an 8 in^3 gun, but stunning of lobster was observed (pers. Comm., J. F. Payne, DFO Newfoundland Region).

2.1.2.2 Behavioral changes

Indirect observations on behavioral changes in invertebrate species caused by marine noises are limited to commercially exploited species e.g., snow crab, mantis shrimp, Norway lobster, short-finned squid, and other mollusks. These studies focus mainly on changes in catch rates by conventional fishing gears. Some results are difficult to interprete considering that certain species may be attracted to the site of a blast or shooting to feed on the dead and injured animals (Trudeau, 1979). This effect makes it difficult to determine the relationship between catch rate and abundance in these areas.

Steffe and Murphy (1992) analyzed historical trends in monthly catches of king prawn and compared them with pre-, during and post-seismic survey catch rates of selected fishermen. No significant difference in catch rates of king prawn was observed before, during or after the seismic survey operations off Newcastle, New South Wales, Australia (Tables 15, 18, 19).

La Bella et al. (1996) reported that no apparent changes in trawl catches were found in short-finned squid (*Illex coindetti*) nor in Norway lobster (*Nephrops norvegicus*) in the area prospected one day before at sound source levels of 210 dB re 1µPa at 1m (corresponding to levels of 149 dB re 1µPa at fish location*). The same authors reported that no apparent catch reductions in Mantis shrimp (*Squilla mantis*) caught by gill nets, and in Golden carpet shell (*Paphia aurea*), Inaequivalvis ark shell (*Anadara inaequivalvis*), and Purple die murex (*Bolinus brandaris*) caught by a hydraulic clam dredge in the area prospected one and two days before exposed to the same sound level mentioned above. However, a gastropod, Purple die murex (*Bolinus brandaris*) caught by gillnet showed a significant difference in catch rate. Based on the results of catch comparison of this species between hydraulic dredge and gill nets, the author concluded that this is a change in behavioral reaction to seismic guns rather than immediate mortality (Tables 16, 18, 19).

Christian et al. (2003) showed no effects on catch rate of snow crab (*Chionoecetes opilio*) by comparing pre- and post-seismic testing. The catch rates were even higher in post-seismic fishing than pre-seismic fishing (Tables 13, 16). The authors concluded that this was likely due to physical, biological or behavioral factors unrelated to the seismic source.

Anecdotal information

Boudreau et al. (1999) quoted anecdotal evidence from a snow crab fisherman operating off Newfoundland that catches declined in the immediate vicinity of a seismic survey but there was no decline at a distance of 50 nautical miles. Similar observations were reported by Thomson et al. (2001b) that there was an incident in NAFO Divisions 3NO where crab catches dropped sharply after a seismic exploration program in the area yet the catch reductions were not noted in more distant areas (Author's note: these authors may be reporting on the same seismic survey).

The catch data from two shrimp (*Pandalus borealis*) trawlers (Soldal and LØkkeborg, 1993 cited in Dalen, 1994) showed a 60% increase of the shrimp catches of one vessel immediately after a seismic operation started while there were no changes in catch rates of the second vessel. No changes were found in the by-catch of Greenland halibut (*Reinhardtius hippoglossoides*), while the by-catches of cod were reduced by 80-85% on both vessels during the seismic operation period. (Authors' note: the original article written in Norwegian could not obtained and was not examined in this document but was cited in Dalen's (1994) description).

2.1.2.3 Morphological, biochemical and physiological changes

Study on the physiological effects by seismic air-guns on invertebrate species is extremely limited compared to other marine animals (Santulli et al., 1999 for review). Only two articles dealt with physiological analysis on invertebrates exposed to seismic air-guns.

La Bella et al. (1996) compared hydrocortisone, glucose and lactate levels in *Paphia aurea* and reported that the difference of the results between test and control animals indicated an evident response to acoustic stress (Tables 18, 19).

The recent article by Christian et al. (2003) published the effects of seismic energy on snow crab (*Chionoecetes opilio*), which examined a series of morphological and physiological characteristics i.e., haemolymph, hepatopancreas, heart, heads (statocysts, green glands, and brains), gills and gonads. They did not find significant effects on the physiological components of tested animals, but they noted that embryonic develoment of external eggs may be delayed after being exposed to seismic air-guns (Tables 13, 19).

3. Overall Summary

3.1 Scarceness and incompleteness of the information on invertebrates

The study on the effects of marine noise on invertebrate species is extremely limited and incomplete. In addition, Gausland (2000) mentioned that ‘many reports on behavioral change caused by seismic surveys are difficult to compare, because measurement methods and units are not documented properly. Unfortunately, there is no clear rule for defining sound levels that will inflict behavioral change, which leaves interpretation of the reports highly subjective’.

We have found 35 articles dealing with the original study on the possible effects of marine noise on invertebrates, most of these are secondary or gray publications produced as internal industry reports, governmental technical reports, and other non-journal sources. Two sources of noise have been studied. The first, refractive seismographic surveys by explosives were examined in 15 articles. Nine of these described quantitative tests, two consisted of article reviews and two consisted of anecdotal information. All documents dealing with seismographic surveys with explosives are in general incomplete and lacking of the measurement of the sound source and received levels. Keevin and Hampen (1997) based on their thorough literature review criticized that these earlier invertebrate mortality studies “*have used inadequate sample sizes, lacked adequate controls, and failed to conduct pressure waveform analyses of the explosion. In addition, investigations have failed to give adequate information concerning testing conditions*”. Comparing of the effects caused by explosive and air-guns is impossible because there is no consistent way to measure noise level generated by the two methods. Although these articles are often cited in recent reviews of seismic effects on marine invertebrates (e.g. McCauley, 1994; Anonymous, 2004a), seismographic surveys using explosives are outdated method and do not add additional information to this study.

The second, seismic surveys with air-guns were examined in 20 articles. Nine of these described quantitative tests, five consisted of anecdotal information and three had additional information to the existing document. Among documents dealing with seismic air-guns, 3 publications were refereed but not based on original studies. For example, Norris and Møhl (1983) dealt with the behavior of odontocetes by citing unpublished results by Møhl et al. on the behavior of odontocetes prey (squid) but without providing any detail of the experimental design and full results. Wardle et al. (2001) examined fish behavior with some coarse observation of invertebrate behavior but without any species names. Hirst and Rodhouse (2000) provided the estimation of received sound level to La Bella et al.’s (1996) work.

The results of nine quantitative studies based on the summary by species and by sampling type showed five cases of immediate (lethal or physical) impacts and four cases of no impacts. One showed a case of physiological impacts and one article showed no physiological impact. Three cases showed behavioral impacts and one article showed no impact on behavior.

Summary of impacts of seismic air-guns on marine invertebrates based on literature reviews

	Lethal/Physical	Physiological/ Pathological	Behavioral	Catch rate
Negative	*Loligo vulgaris* *Chionoecetes opilio* (eggs) *Chlamys islandicus* Sea urchins *Architeuthis dux*	*Bolinus brandaris*	*Alloteuthis sublata* *Sepioteuthis australs* *Architeuthis dux*	*Bolinus brandaris*
No impact	*Chionoecetes opilio* *Mytilus edulis* *Gammarus locusta* *Crangon crangon*	*Chionoecetes opilio*	*Chionoecetes opilio*	*Crangon crangon* *Penaeus blebejus* *Nephrops norvegicus* *Illes coindetti* *Squilla mantis* *Paphia aurea* *Anadara inaequivalvis*

Very limited numbers of experiments were scientifically and reasonably conducted. Squid (McCauley et al., 2000 a) and crab behavior (Christian et al., 2003) have been studied by direct observation. Pre- and post seismic air-guns comparisons of catch rates were made by La Bella et al. (1996) and Christian et al. (2003) on various invertebrate species. The quantitative and anecdotal aspects of all other studies were inadequate for assessing the effects of explosives and seismic air-guns on invertebrates. In addition, in-depth analyses on physiological changes in animals exposed to seismic air-guns are quasi-absent.

Further research is needed by considering the following subjects:
Impacts on animals:

1) Immediate and delayed behavioral and lethal effects e.g., alternated seasonal movement patterns;
2) Immediate and delayed pathological effects e.g., alternated hearing, sighting, growth and mating capacity;

Spatio-temporal considerations:

1) Cumulative effects of multiple disturbance displaced in time and space e.g., exposure of long duration and repeated exposures over time;
2) Timing of seismic survey versus timing of sensitive period of the life cycle event;

Ecosystemic consideration:

1) Indirect impacts on the animals exposed to seismic noise such as increased vulnerability to both disease and predation e.g. due to loss of hearing capacity and immune system.;

Survey design has to be properly set by preparing enough numbers of replicate with test and control groups. The measurements of received acoustic sound by animals are essential to compare the results obtained by other studies and set the threshold level of noise for each studied animal. The obtained results have to be tested by statistical analyses for the significance. When assessing the differential catch rate of animals between pre- and post-seismic testing, it is recommended to deploy different gear types i.e., both active and passive gears so that more detailed information can be obtained e.g., La Bella et al. (1996) who used hydraulic clam dredge and gill net to assess catch rate of a gastropod. All information relative to the study i.e., date and duration of the study, environmental parameters, site specific information (depth, temperature, current, salinity etc.), have to be described as precise as possible, which were commonly laking in literature reviewed in this document.

3.2 Authors' comments on literature dealing with seismic air-guns

The description of tolerance and behavior of two species of squid by Norris and MØhl (1983), based on the citation of unpublished work by Møhl et al., was incomplete. There were no details of the distance between the air-gun and the test animals; no observations on the control animals; no behavior observations vis-à-vis different sound levels; no individual results of their 17 and 5 trials on *Alloteuthis subulata* and *Loligo vulgaris*, respectively and no physiological examination of dead animals.

Kosheleva's (1992) conference abstract has often been cited by many authors. However, the abstract does not contain detailed information, but referred to the original document in Russian for the details. The reference of this original document was not traceable and none of documents cited this original document. Turnpenny and Nedwell (1994) who were the authors estimated the source and received sound levels. All other authors who mentioned Kosheleva's work cited Turnpenny and Nedwell (1994). Dalen (1994) gave some clarification of the testing procedures and species latine names. In our document we combined data from these two sources in addition to Kosheleva (1992). The citation of Kosheleva's (1992) work by Turnpenny and Nedwell (1994) was again cited by Davis et al. (1998), Thomson et al. (2001b) and Collins et al. (2002). Although the work done by Kosheleva (1992) has been frequently cited by many authors, the cited descriptions of the results differ. Dalen (1994) cited Kosheleva's work (1992) as follows: From the literature only one experiment with air-guns and planktonic organisms is known (Kosheleva 1992). The species used were benthos represented by gammarids, (*Gammarus locusta*), gastropods (*L. obtusata*) and (*L. littorea*), the mollusks (*Mytilus edulis*), and zooplankton species of higher and lower crustaceans. Only the test on the gammarids and the mollusks were successful. No significant harmful effects were observed at distance of 0.5 m and greater from single gun (chamber volume 3.0 l) for the gammarids and the mollusks. Whereas, Davis et al. (1998), Thomson et al. (2001a) and Collins et al. (2002) cited the citation by Turnpenny and Nedwell (1994) of the same work by Kosheleva (1992) as follows; In the Barents sea, single air-guns of 60-180 in^3 and arrays of these air-guns with source levels of 220-240 dB re 1 μPa. m$_{0\text{-}P}$ had no effect on phytoplankton or benthos at distances of 1 m or more from the source. The abstract of Kosheleva's conference presentation stated that 0.5 m from the seismic source is a safe distance for benthos. The author tested both phyto- and zooplankton but did not describe the results on zooplankton and did not mention the seismic source i.e. single or combination of air-guns in the abstract. The source and received levels of air-guns were not given by Kosheleva (1992), but estimated by Turnpenny and Nedwell (1994). Anonymous (2002b) and Christian et al. (2003) mentioned "crab" as a tested animal by Kosheleva (1992), but none of other documents mentioned of "crab" including Kosheleva (1992).

Matisov's (1992) work on sea urchins and Iceland scallop is not detailed enough (e.g., no sound source type, sound source or received levels, no study design, no mention of the number of sample, no physiological examination of affected animals). Anonymous (2002b) described an estimated source level at 233 and received level of 217 dB.

Steffe and Murphy (1992) compared the commercial king prawn catch rate pre- and post-seismic survey period and concluded that they could not detect any impact on offshore prawn catches that could be due to the seismic survey. However, no statistical analysis for the catch comparison was made. Source type, source level, exposure level, and other details of the seismic survey were not given. This document provided not more than anecdotal information.

Webb and Kempf (1998) concluded that after seismic testing in shallow salt marshes in the Wadden Sea, no mortality or catch rate reduction of brown shrimp (*Crangon crangon*) was observed. However, the authors did not describe the sampling design or analytical methods for mortality and catch rate studies, or provide any details on the results. Thomson et al. (2001b) cited Webb and Kempf (1998) "*Webb and Kempf (1998) exposed brown shrimp in the Wadden Sea to an array of 15 air-guns with a total volume of 480 in^3 and a source level of 190 dB re 1μ Pa at 1 m in 2 m water depth*". However, there was no clear mention by Webb and Kempf (1998) about the water depth of tested area except for the following '*In the shallow waters of the Wadden Sea (ca. 2 m) however, transmission loss i.e. the rate of sound decay is high due to boundary losses at the water surface and into the seabed*'. In addition, the authors found it difficult to operate in shallow-water areas with an array of 15 air-guns and a total volume of 2000 psi. To overcome this difficulty they used a smaller version of air-guns (an array of 9 guns with a total volume of 320 in^3 operating at a pressure of 2000 psi) and a vibroseis (one vibrator). However, they do not provide information on which type of sound source was used to make the observations.

La Bella et al. (1996) provided pre- and post-seismic air-gun survey catch rate comparisons. The pre-seismic catch rate differed from post-seismic one for one species of gastropod. In addition, there was some indications of stress in a bivalve (no other invertebrate species tested in this work was examined for their physiological response). However, these two possible effects of seismic air-guns have never been cited by any other documents.

McCauley et al. (2000a) described detailed observations on the behavioral reaction of squid to air-gun surveys. However, no physiological or anatomical observations on the test animals were made despite that the authors planned to study possible pathological damage of the statocyst organ.

Christian et al. (2003) provided the most elaborate information on the possible effects of seismic air-guns on invertebrates (snow crab). However, a full description of the results of histological and anatomical examinations on sampled tissues (heart, green glands, and brains, gills and gonads) was not given and only thread hairs in the statocysts were observed. They indicated there may be a delay in embryonic development for test eggs compared to control eggs, but the sample number is insufficient (one test clutch of about 2000 eggs and one control of the same number).

We consider the paper by Soldal and Løkkeborg (1993) as anecdotal information because we could not obtained the original document. In addition we could not find any citations of this work other than in Dalen (1994). The description by Dalen (1994) was not complete (source type, source level, exposure level, detail of the seismic survey as well as specifications of statistical tests on catch rates and mortality rates). However, Løkkeborg and Soldal (1993) published the study on the effects of seismic exploration on cod. The results were obtained from shrimp trawling off the coast of Finmark and near Bear Island, Barents Sea (both in water depths of 200-300 m). If the authors (Soldal and Løkkeborg, 1993) examined the impacts on shrimp from the same survey, the sound source type used should be an array of 20 sleeve guns with 40 in^3 each and an array of 40 air-guns with total volume of 2660 in^3 (source level of 239-250 dB re 1µ Pa-m. and exposure level of 160-171 dB re 1µ Pa based on Turnpenny and Nedwell, 1994). These surveys were conducted for 2-6 and 3 days, respectively.

We found that the documents by La Bella et al. (1996), McCauley et al. (2000a) and Christian et al. (2003) provided the most elaborated and useful information on the possible impacts of seismic air-guns on invertebrates among the documents examined herein.

3.3 Building premature conclusions without robust evidence

There is a limited number of articles dealing with seismic effects on marine invertebrates. The information is often misunderstood, misquoted or misinterpreted possibly because these papers (mostly gray literature) are difficult to obtain and many authors depend on citations in other publications (see Kosheleva's case in this document). Keevin and Hempen (1997) noted that the paper by Gowanloch and McDougall (1944) was cited by many authors; however, it is usually mis-referenced as a publication in 'Oil' instead of in 'Louisiana Conservationist'. This citation is an example of the danger of depending on secondary citations for accurate descriptions of experiments and conclusions. Another example is that Anonymous (2004a) cited that "*Keevin and Hempen (1997) reported that there was no apparent effect on lobsters exposed to explosiosn from seismic operations*". However, Keevin and Hempsen (1997) never conducted any study on lobster, but cited Knight's (1907) first description of the effects of explosives on the American lobster (*Homarus americanus*). Knight's (1907) study concluded that "*there was* *no result*" but "*it seemed to have no effect on the lobsters*". Keevin and Hempen (1997) also cited Aplin's (1947) work on spiny lobster (*Panulirus interruptus*) by criticizing that "*Because of the small sample sizes and lack of controls, no conclusions can be made from this study*".

Few studies of seismic effects on invertebrates allowed definitive conclusions to be made. Anonymous (2002a) cited Norris and Møhl (1983), further interpreted this work that *if this study is confirmed by further work, these levels would suggest that squid would only be killed within a few meters of individual large or an array of air-guns*. Anonymous (2001a) further concluded that "*The majority of invertebrates are only able to hear seismic survey sounds at very close range (<2m) due to their physiology. Experiments on shrimp, crustaceans and benthic mollusks show no obvious effects and no change in catch-rate"* without showing any citations. Anonymous (2002b) stated that "*A wide variety of other invertebrate species such as jellyfish, comb jellies, sea stars, and crustaceans are sensitive to low frequency (10-150 Hz) hydro-acoustic disturbances (particle motion induced by sound waves and other sources). These animals would likely perceive the low frequency sound waves emitted from passing air-gun arrays; however, the effect of air-guns firing on these animals is not clear, but likely transitory in nature."* McCauley (1994) stated "*Without any conclusive experiments, the actual response of marine invertebrates to 'seismic shot' is largely unknown, but may consist of little more than an alarm response such as the closing of inhalant siphons in sponges and ascidians, to the 'tail flip' response in crustacean"*. However, based on our literature review, there was not enough supporting studies to determine the persistence of effects (transitory or long-term). These types of conclusions made without any robust evidence are cited by others (e.g. Davis et al., 1998; Anonymous, 2001b; Thomson et al., 2001b; Anonymous, 2002c; Collins et al.,2002), which results in a belief that invertebrates are robust vis-à-vis seismic testing.

La Bella et al. (1996) is the one of most cited sources on the possible seismic effects on invertebrates examined by comparison of pre- and post-seismic catch rates of various invertebrates. Many authors (e.g., Anonymous, 2002a) cited this paper to support the conclusion that "*there is no apparent effect of seismic testing on the catch rate*". (*They cited Hirst and Rodhouse' (2000) citation of La Bella et al. 1996). However, La Bella et al. (1996) reported that there were signs of stress found in a gastropod for which physiological examination were made. The same authors also described that catch rate of a gastropod was significantly reduced the day after the air-gun survey and concluded that the motility of this species was affected. These findings by La Bella et al. (1996) have never been cited by any authors.

Anonymous (2002a) stated that "*crustaceans are though to be insensitive to sound which they detect through mechanoreceptors"*. However, based on a series of study on sand shrimp by Lagardère and collaborators (see introduction in this document), this statement may not be true. They also stated by citing Hirst and Rodhouse (2000) that "*most invertebrates would only detect seismic shots within about 20 m"*. Hirst and Rodhous (2000) made this statement based only on La Bella et al.'s (1996) experiment on Norway lobster trawl and mantis shrimp gill netting catches. However, the results of gill net experiment on a gastropod showing possible seismic effect (on the fishing ground at depth of ca. 15 m) were not considered.

Anonymous (2004b) also concluded that "*Data on the impact of seismic shooting on macro-invertebrates (scallop, sea urchin, mussels, periwinkles, crustaceans, shrimp, gastropods, squid) show that little mortality occurs below sound levels of 220 dB. Some show no mortality at 230 dB. For bottom-dwelling species, these data suggest no significant impact for seismic surveys provided the water depth is greater than about 20 m. Cautions should be added regarding key species not among those tested.*" The "safe range of about 20 m" seems to have become a strong conclusion by appearing in citation by many authors (e.g. Davis et al., 1998; Thomson et al., 2001a; Anonymous, 2002c). Although no robust evidence has been demonstrated in the literature reviewed. The origin of this description may have come from McCauley (1994) who stated that "*The majority of marine benthic invertebrates will only respond to seismic sources at extremely close range. This means that only surveys run in very shallow water will have any effect. A conservative figure for the minimum depth for a response would be at 15 m from the array. This range of effect is a crude approximation only, should be verified experimentally and may be greater or less than 15 m. Although large arrays are not used in water less than 20 m deep, smaller arrays with lower source levels may be used*".

3.4 Conclusion

Under the current knowledge on the possible effects of marine noise (seismic air-guns) on invertebrates, there is not enough robust scientific evidence to draw any conclusions (either positive or negative). Often the conclusions on the possible effects of seismic air-guns on invertebrate species were based on the pure assumption without any robust evidence, which resulted in an unverified hypothesis that invertebrates are robust vis-à-vis seismic testing. All speculative description and opinion of the effects has not to be made and all concerned documents have to be thoroughly examined to properly cite the results of previous studies in order to avoid any misunderstandings or misconceptions. Marine invertebrates are important members of the marine habitat, food web, and ecosystem.

Comprehensive research programs should be instituted to thoroughly investigate the possible effects of seismic activity on various marine invertebrates in order to buildup the scientific knowledge on this subject.

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4.1 Summary tables

4.1.1. Effect of shock waves (refractive seismic surveys with explosives)

Table 1. Gowanloch and McDougall (1944 and 1945)	
Where	Louisiana, USA
When	1944-45
Species	*Penaeus setiferus, Crassostrea virginica*
Study Type	Experimental
Sound Characteristics Source Type	200-800 pounds of 60% gelatin dynamite No pressure measurement available
Experimental Design	First study (1944): 200-800 pounds of 60% gelatine dynamite was placed on the ocean floor in the depth of 18 feet. Oysters and crabs were placed (separately) in slatted wooden cages (30 in^3) midway between surface and bottom. Animals (45 shrimp and 30 oysters) were placed at 50, 100, 150, 200 and 300 feet from the shot point 48 hours prior to the shot and were examined immediately after the explosion and 24- and 48 hours post-detonation. Control animals were placed far beyond any possible influence from the dynamite blast. Second study (1945): the same condition as the first study but cages containing oysters were put on the bottom. No statistical analysis was made.
Effects Mortality	 Shrimps were uninjured at 50 feet regardless the amount of explosive. No conclusive mortality data was obtained for oysters (first study). Seismographic explosions caused no subsequent mortality to the oysters (second study).

Table 2. Aplin (1947)	
Where	Southern California, USA
When	1944-45
Species	*Haliotis corrugata, Haliotis fulgens, Panulirus interruptus*
Study Type	Experimental (caged animals)
Sound Characteristics Source Type	A 20-pound charge placed 4 feet under the surface. No sound pressure was measured.
Experimental Design	For abalone: A 20-pound charge fired 4 feet below the surface on 8 abalones (4 for each species) at sizes ranging from 100 to 175 mm placed on the bottom at 55 feet in depth. Two experiments for spiny lobsters: 1) 8 lobsters ranging 27 to 30 cm in length exposed to a 20-pound charge fired 4 feet under the surface. Lobsters were placed on the bottom at 55 feet, 2) 13 lobsters ranging from 17 to 23 cm were exposed to a 20-pound shot fired 4 feet below the surface. Lobsters were place at 4 feet below the surface but at the distance of 50 feet from the center of explosion. No control animals were used for this study. No statistical analysis was made.
Effects Mortality	The shell of one abalone was broken (but cause is not certain). All abalones were dead within a few hours after the explosion. First experiment: Five hours post exposure the lobsters were all alive and active. Second experiment: Three hours after the explosion, the test lobsters were alive and no signs of damage were found in the internal organs.

Table 3. Anonymous (1948)	
Where	Chesapeake Bay, Maryland, USA
When	1944-45
Species	*Crassostrea virginica, Callinectes sapidus*
Study Type	Experimental (Caged animals)
Sound Characteristics Source Type	DuPont Nitramon, TNT with 1 pound Nitramon No measurement for pressure for the oyster study was provided.
Experimental Design	Six experiments for oysters: 1) 5-pound charge fired followed by 27-pound at 30 feet in depth on caged oysters at 40 feet in depth. Oysters were placed at 100, 200, 300, 400 and 700 feet from the center of explosion. ; 2) a 31-pound suspended Nitramon was fired on oysters placed directly on the bottom at ca. 35-40 feet. Oysters were place at 25, 50, 100, 150, 300 feet from the center of explosion, 3) a 30 -pound suspended charge was fired on oysters in bags on the bottom. Oysters were placed in 29, 73, 129, 225 and 381 feet from the center of explosion. Control bags were also used., 4) a 300-pound TNT suspended at 15 feet below the surface fired on oysters (dredged 2 weeks before the testing and placed on the bottom 4 hrs before the testing) in bags at 30 feet in depth. Oysters were placed at 25, 50, 100, 200, 400 and 960 feet from the center of explosion. Control bags were placed. 5) a 300-pound TNT was suspended at 15 feet below the surface and fired on oysters (caught and placed prior to the testing) that were put in bags on the bottom at 30 feet. Oysters were also placed at 25, 50, 100, 200 and 400 feet from the center of explosion. Control bags were placed., 6) a 30-pound charge fired on oyster put in a metal framed wire cages suspended in depth of 22 feet in 30 feet of water. Oysters were placed at 20, 30, 80, 150 and 200 feet from the center of explosion. Oysters were also observed several weeks after the explosion. No statistical analysis of the data was conducted. One experiment on blue crab: A 30-pound charge was fired and blue crabs were placed in cages at 25, 50, 75, 100, 125 and 150 feet from the center of explosion.
Effects Mortality	 Slightly less than 2% of the oysters exposed to charges of 27-31 pounds within a 100 feet radius were gaping. This happened only for suspended cages. Using charges of 300 pounds, less than 2.2 % were killed within 200 feet of the charge. Two weeks loss was estimated at 5.4% compared to 0% for control excluding single dead oyster at a distance of 960 feet. 90% of crabs were killed within 25 feet from the center of explosion corresponding to 800-900 pounds/in^2 but very few died at 150 feet with corresponding pressure of 270 pounds/in^2.

Table 4. Sieling (1951 and 1953)	
Where	Bay Batiste, Hackberry Bay, Texas USA
When	1949-1950
Species	*Crassostrea virginica*
Study Type	Experimental (animals placed on racks)
Sound Characteristics Source Type	50-pounds of Nitramon placed at 70 feet and 20-pounds at 30 feet depth in each hole (under the ocean bottom). No measurement of pressure.
Experimental Design	Two experimental design: 1) oysters were placed on racks above the bottom and exposed to two different charges of explosive. Control stations were located 750 feet from the nearest shot point. 2) oysters were placed in trays and put on the bottom and exposed to two different charges of explosive. The immediate mortality was compared among the different treatment and control. In addition glycogen analyses were conducted for test and control animals. The specimens were kept at test and control sites for a period of eight months after detonation.
Effects	
Mortality	50-pounds at 70 feet underground test: Sinking, if any, between test and control oysters did not differ. Oysters from 40 feet from the explosion center were not covered by silt or affected by sediment or any turbidity caused by preparation of the testing. Oysters placed at 40 feet from the explosion center did not suffer from any abnormal mortality for a period of 8 months. Oysters in trays 20, 60, 130 and 250 feet from the shot point that were kept for a period of 4-8 months after the explosion did not have a higher mortality than control animals. Oyster in trays brought from the control site and placed in test site at 20, 60, 130 and 250 feet from the shot point after the explosion did not differ significantly in mortality among themselves or from those exposed to explosion and remained in place. There was no correlation between the distance of the oyster from the explosion and the survival rate.
Physiological	Glycogen analyses did not show any consistent trend, which indicates no physiological disturbance among the oysters exposed to different conditions.

Table 5. Kemp (1956)	
Where	Corpus Christi Bay, Texas, USA
When	1956
Species	*Penaeus seliferus, Callinectes sapidus, Crassostrea virginica*
Study Type	Experimental (Caged animals)
Sound Characteristics Source Type	40-pound charge of Nitramon at the depth of 20 feet below the ocean bottom. No pressure measurement was made.
Experimental Design	Crustacean specimens were held in 1/2 inch mesh hardware cloth cages and oysters were put in heavy wire trays and placed on the bottom. In each test, one set of specimens (25 shrimp, 25-47 oysters, 2-4 crabs) was placed at the shot hole and 25, 50, 100 and 200 feet from the shot point. A set was also placed at 1/4 and 1/2 mile away as a control (25 shrimp, 38 oysters and 2 crabs). In addition, for the test-1, animals were also suspended 3 feet below the surface. Test-1: At depth of 13 feet on the very soft, gray muddy bottom. Test-2: At depth of 2 1/2 - 3 feet on the hard sandy bottom. Test-3: At depth of 7 feet on soft and gray muddy bottom.
Effects Mortality	Shrimp and crabs were found to be completely immune to underwater explosion, since they suffered no ill effects whatsoever during the test. The damage to oysters was most severe within a 25 feet radius of the blast and some dead oysters were found as far as 200 feet. If the minimum distance from an oyster reef were extended from 300 to 500 feet, it would probably afford a more comfortable safety margin.

Table 6. Anonymous (1962)	
Where	North of the Alsea River, Oregon, USA
When	1962
Species	*Cancer magister*
Study Type	Experimental (caged animals)
Sound Characteristics Source Type Exposure Duration	5-lbs (2 feet beneath the surface) and 25-lbs (4 feet beneath the surface) of nitro-carbonitrate. No pressure measurement was available.
Experimental Design	Small crabs (< 80 mm max.) and large crab (>130 mm min.) were caught in tide pools six weeks prior to and by commercial crab pots a few day prior to the experiment, respectively. 8 crabs (assortment of 3 large hard shell, 3 large soft shell and 2 small soft shell, or similar) were put in a cage (commercial trap) to make 12 tests and 3 controls. Chelae of all crabs were tied with rubber bands. Five pounds of charge, suspended at 2 feet beneath the surface, exploded over 2 crab pots placed at water depth of 8 and 15 fathoms. Twenty-five pounds of charge, suspended at 4 feet beneath the surface, was exploded over 2 crab pots at water depth of 35 fathoms. The same condition was repeated for the following additional tests: Five pounds of explosive, suspended at 20 feet beneath the surface, was exploded over 2 crab pots at the water depth of 8 and 15 fathoms. Twenty-five pounds of explosive, suspended at 40 feet beneath the surface, was exploded over 2 crab pots at water depth of 35 fathoms. One pot was recovered and crabs were examined at each depth in both series within 30 minutes after the explosion. The remaining pots were recovered after 96 hours. Divers examined the condition of crabs on the bottom and at the 8 and 15 fathom depths of both series prior to recovery and immediately following the blasts. Three of 15 pots were placed on the bottom in the study area and retrieved at 96 hours. After the blast one pot was placed approximately 100 feet from the remaining test pots for each depth of the first series. The results of control vs. test, immediate recovery (30 min.) vs. delayed recovery (96 hrs) were examined.
Effects Mortality	For all four variables (crab sizes, charge sizes, cage depths and carapace condition): 1) There was no significant difference in the mortalities or damage between the test and control groups., 2) There was no significance in mortalities or damage with the crab pots placed at different depths., 3) There was no significance in numbers of mortalities or damage between surface and submerged shots., 4) There was no significant difference in the numbers of crabs dead or damaged between 5 and 25-lb charges.

Table 7. Linton et al. (1985)	
Where	East Bay, Texas, USA
When	1981
Species	*Penaeus seliferus, Callinectes sapidus, Crassostrea virginica*
Study Type	Experimental (Caged animals)
Sound Characteristics Source Type	A 33-meter strand of 100 gram/foot Primacord detonation. No pressure measurement was made.
Experimental Design	The study site was in a shallow water bay system (2.5 m in average depth) of the upper Texas coast and consisted of soft, mud and oyster shell reefs (water temperature at 6°C and salinity at 12ppt). Animals (white shrimp, 23 cm in average; blue crab, 8.5 cm in average; and oysters greater than 15 cm) were placed in cylindrical cages (90 x 75 cm enclosed with 1.8 cm nylon mesh webbing, and for shrimp cages 0.5 cm nylon mesh liner was added). Ten (10) crabs and 10 oysters were placed in the same cage and 10 shrimp were placed separately. A line of cages (surface and bottom sets except for oysters using only bottom cages) were placed at logarithmic distance of 1, 11, 23 and 46 m from the detonation line placed perpendicular to the cage line forming a T-shape. The lines were verified immediately after 24 hours after the detonation to verify the mortality. Control array of cages, using the same set-up of organisms and cages for test sites, were also placed out of test site (136 m from the detonation site). In addition, control animals were received the same treatment as test animals, with the exception that they were not in the water at the time of the explosion (cages were removed from the water seconds before detonation and returned shortly thereafter). After detonation, the animal mortality was verified (oyster: shell permanently agape; shrimp: cessation of gill movement). Dead animals were transported to laboratory for internal examination, with the exception of live oysters being transported to other site for monitoring of after effects for a 2-week period.
Effects Mortality	White shrimp suffered mortalities in all test cages and depths, but exhibited no well-defined pattern relative to survival and distance from detonation site. Survival of blue crabs in bottom cages was directly related to the distance from the site of detonation. Mortality, ranged from 40% at 1 m to 10% at 46 m from the detonation site. Survival of American oysters was high and inversely related to distances from the center of detonation between 95% at 1 m and 85% at 23- and 46 m from the detonation site. Total mortality of oysters after 24 hours of the detonation at each site 1-11-23 and 46 m from the detonation center was: 10-35-30-0 % for white shrimp, 60-50-35-10 % for blue crab, and 5-5-15-15% for oysters. Total mortality of the control group was 0% for all sites.

4.1.2. Effects by seismic air-guns

Table 8. Norris and Møhl (1983)*	
Where	Not mentioned
When	Not mentioned
Species	*Alloteuthis subulata, Loligo vulgaris*
Study Type	Experimental (Direct shooting on the animals)
Sound Characteristics	
Source Type	Not mentioned
Source Levels	Up to 260 dB re 1µPa
Exposure Levels	Not mentioned
Exposure Duration	Not mentioned
Experimental Design	17 trials on *Alloteuthis subulata* (mantle length 4 cm) exposing up to 260 dB re 1µPa high rise-time shocks, and 5 trials on *Loligo vulgaris* (mantle length 18-27 cm).
Significance	Not mentioned
Effects	
Physical	*Alloteuthis subulata* showed short-term tolerance, but *Loligo vulagrais* were fatally injured by peak pressures of 246-252 dB re 1µPa and died within 3-11 minutes after being exposed to the sound noise.
Behavioral	
Physiological	Not studied

***** B. Møhl, K.S. Norris, P. Norris and K.J. Staehr, MS

Table 9. Kosheleva (1992)	
Where	Ura Gaba Inlet, Barents Sea
When	1989 and 1990
Species	*Mytilus edulis, Gammarus locusta*
Study Type	Experimental (Direct shooting on the animals)
Sound Characteristics	
Source Type	Single air gun of 60-180 in^3 (1000-3000 cm^3) and arrays of these
Source Levels	airguns with source levels of 220-240 dB re 1μPa.m $_{0\text{-}P}$
Exposure Levels	Up to 220 dB re 1μPa*[1]
Exposure Duration	Not mentioned
Experimental Design	The test organisms were suspended in cages at three specific distances from the gun mouths- at 0.5, 1.0 and 2.0 m. The control group was also examined. 18 series of exposure to the shock waves created by air pulses were conducted, and each was followed by test for signs of impacts, starting with visual observation for outward signs of injury and changes of behavior and concluding with the killing of the specimens and exhaustive physiological examination.
Significance	No results of physiological test mentioned. No statistical test was done. The control group was set.
Effects	
Physical	Tests on gastropods were not successful*[2], but no apparent impact was
Behavioural	observed on benthos (mollusks and crustaceans) at the distance of 0.5 m
Physiological	Not mentioned

*[1] From Hirst and Rodhouse (2000), *[2] From Dalen (1994)

Table 10. Matishov (1992)

Where	Barents Sea
When	1989
Species	*Chlamys icelandicus, Seaurchins*
Study Type	Experimental (Direct shooting on the animals)
Sound Characteristics	
Source Type	Single air-gun
Source Levels	Source level of 223 dB re 1μPa*
Exposure Levels	Received level of 217 dB re 1μPa*
Exposure Duration	Not mentioned
Experimental Design	Caged animals were exposed to a air-gun fired once at the distance of 2 meters.
Significance	No control was set. No statistical test made. The sample number is low (3) in Iceland scallop and no mention of the number of sample for seaurchin. Not useful for the assessment of impact.
Effects	
Physical	The shell of one of three mollusks (Iceland scallop) split and 15% of the spines in seaurchins fell off.
Behavioural	Not studied
Physiological	Not studied

* from Anonymous (2002b)

Table 11: Webb and Kempf (1998)	
Where	Wadden Sea
When	1996-97
Species	*Crangon crangon*
Study Type	Observations
Sound Characteristics	
Source Type	Array of 15 air-guns with a total volume of 480 in^3 operating at a pressure of 2000 psi
Source Levels	230 dB re 1μPa at 1 m to 250 dB re 1μPa at 1 m for a single air-gun and an array, respectively.
Exposure Levels	190dB re 1μPa at 1 m in 2m water depth.
Exposure Duration	Firing once every 12-17 seconds (ca. every 25 m)
Experimental Design	Aiming to update some of the misconceptions concerning the impacts of shallow-water seismic operations on sand shrimp. Underwater sound was monitored using hydrophones and associated equipment taken over ranges from 65 m to 4500 m. No detailed sampling protocol.
Significance	No control group used. No detailed results and no statistical tests shown. Not useful for assessing the impact on sand shrimp.
Effects	
Physical	No mortality found.
Behavioral	No evidence of reduced catch rates
Physiological	Not studied

Table 12: McCauley et al. (2000a)	
Where	Jervoise Bay, South of Fremantle, Australia
When	July 1997 and April 1998
Species	*Sepioteuthis australis*
Study Type	Experimental (caged animals)
Sound Characteristics	
Source Type	One Bolt 600B air-gun with 20in^3 chamber
Source Levels	Gas pressure of 10-11 MPa (1500-1600 psi)
Exposure Levels	139 to 184 dB re 1μPa
Exposure Duration	Between 22 and 61 minutes for each continual set of air-gun shots (sudden nearby startup and ramped up approach)
Experimental Design	Three trials were carried out primarily to gauge behavioral effects to nearby air-gun operations. Trial design: 1) 12 squids (mean size at 166 ± 23 mm and acclimated for 7-18 days prior to the testing) and 2 cuttlefish (no size information acclimated for 16 days) were placed in fixed floating pens (6 x 6 x 3 m) and exposed to an air-gun operated from a morred pontoon 10-30m off the sea cage (2 tests). Air-gun pressure raised or dropped accordingly (exposure duration of 59m50s and 1h01m30s separated by 1h26m25s). 2) For a greater dynamic range, 19 squids (mean size at 185 ± 14 mm acclimated for 7-10 days) were placed in fixed floating pens (10 x 6 x 3 m) and exposed to an air-gun operated from a towed pontoon. Approach-departure was achieved by towing the air-gun pontoon towards and away from the sea cage from normally 350-450 m start range to 5-15 m closest approach (exposure duration of 48m41s and 22m04s separated by 1h02m32s). 3) Squids (same samples) from trial 2 were exposed again four days later by the towed pontoon (exposure duration of 46m48s and 39m13s separated by 1h11m52s). For the trial 2 and 3, alarm responses in the form of squid jetting away from the air-gun source and corresponding with air-gun shot. The number of these observations was used to estimate the difference ratio (d). The count of startle or response period above threshold (s_p) /total behavioral count period for air-gun threshold periods (S_p) minus the similar ratio (s_n/S_n) for periods with no air-gun operation (i.e., $d=s_p/S_p - s_n/S_n$).
Conditions	Water temperature in Jervoise Bay ranged from 16-20°C (second and third experiments), and from 21-23°C (first experiment) in Exmouth Gulf. Water depth in Jervoise Bay was 9m with a fine, muddy bottom, and 10 m in Exmouth Gulf.

McAulay et al. (2000a) continued

Significance	Mean difference ratios were compared with expected ratio (zero or the same as measured in control periods) using a t-test gave a significant results for each trial and trials #1 and 2 combined with $p<0.005$.
Effects	
Behavioral	Strong startle (ink sac fire) to first start up at received air-gun level of 163 dB re 1μPa^2.s, but not observed for similar or greater levels if signal ramped up. Increasing proportion of startle response (jetting away from air-gun shot) recorded as air-gun signal increased with effect most noticeable above 145-150 dB re 1μPa^2.s Possible trend to move towards water surface (lower air-gun signal zone) as air-gun approached. Evidence of increased swimming speed as air-gun approaches then slow down at air-gun signals greater or equal to 155 dB re 1μPa^2.s
Physiological	No pathological examination of preserved squid statocyst systems has been made but there is a possible pathological damage of the statocyst organ.

Table 13: Christian et al. (2003)

Where	Conception Bay, Newfoundland, Canada
When	Fall 2002
Species	*Chionoecetes opilio*
Study Type	Experimental (Shooting on caged animals), Monitoring of catch rates
Sound Characteristics	
Source Type	Two 10-in^3 sleeve air-guns were used (one 20-in^3 gun and four 40-in^3 guns) either singly (40-in^3) or combined in array of seven guns (200-in^3).
Source Levels	Guns are set at 2 meters below the surface of the water and fired 200 times at 10-second intervals.
Exposure Levels	Exposure levels from 40-in^3 gun: Peak received broadband sound levels of 201-227 dB re 1µ Pa and energy density of 183-187 dB re 1µ Pa^2/Hz at frequencies between 24 and 31 Hz. Exposure levels from the 200-in^3 array: 197-237 dB re 1µ Pa and a maximum energy density of 175 dB re 1 Pa^2/Hz within the 17 to 19 Hz frequency range.
Exposure Duration	2-292 hours for catchability study, 33 minutes for crab health study
Experimental Design	Catchability study: 7 sets of 40 traps (conventional with 14-cm mesh and modified types with 5-cm mesh) were made for pre- seismic shooting period, and 6 sets were used for post-shooting period by using squid as bait.Fishing grounds at depths ranging 165-175 m were exposed to shots with a 7-gun array (200 in^3) with the total number of shots varying from 200 to 1000 with total exposure duration varied between 2 and 292 hours. Crabs were counted, measured and categorized into four groups based on carapace width. Crab behavior study: Six crabs were tagged with acoustic transmitter and they were manually tracked during the test. Video camera was also used to observe potential startle behavior of crabs deployed in cages, first in the water column and then on the bottom in 50-m water. Crab health study: Exposing caged 92 crabs to either the single 40-in^3 gun at 2, 10, 15 m water depths or the 200-in^3 array at 4, 50, 85 or 170-m water depths. Each exposure consisted of 200 air gun shots fired at a rate of one every 10 seconds for a total exposure of 33 minutes. A control group of the same number (92) was handled in a similar manner without seismic air-gun shooting. Crabs were sampled for haemolymph, hepatopancreas, heart, statocyst, green glands, brains, gills and gonads. Haemolymph was analyzed for relative concentration of total dissolved substance in serum, serum protein, serum enzyme activity screening and haematocyte type.

Christian et al (2003) continued

	Egg study: One batch of eggs c.a. 4000 at the same embryonic development stage were divided into two groups and handled in an identical manner. One group was exposed to 200 shots with the 40-in^3 gun at a distance of 2 meters. Eggs were held in aquarium for 12 weeks before examination.
Significance	For the health examination study, the results were subjected to statistical analyses (unpaired t-test or Mann-Whitney Rank Sum test).
Effects	
Physical	No crab was died during the experiments. In some cases, animals seemed more energetic immediately after exposure than the control animals.
Behavioral	Crabs being exposed to the 200-in^3 array being fired 50 m above them showed no readily visible reaction (no mention of water colum observations). Six acoustic tagged crabs were remained with a 200-m radius of the range of hydrophone 48 hours after shooting. The tagged crab did not undergo any large-scale movements out of the area. The results of catchability study showed that post-seismic catches were higher than pre-seismic catches. The authors concluded that this was likely due to physical, biological, or behavioral factors unrelated to the seismic source and concluded that there was no significant relationship between catch and distance from the seismic source.
Physiological	There were no seismic effects on the health of the snow crab based on the biological, chemical and biochemical analyses subjected to statistical analyses. Eggs were exposed to high levels of sound (221 dB at 2-m depth), their development may retard.

Table 14. Guerra et al. (2004)	
Where	North-eastern Atlantic (Biscay Bay)
When	2001 and 2003
Species	*Architeuthis dux*
Study Type	Field and laboratory bservations (Post-seismic incidences of stranding and surface-floting of 9 speciments)
Sound Characteristics	
Source Type	Air gun arrays
Source Levels	Low frequency (100 Hz) and 200 dB
Exposure Levels	Not mentioned
Exposure Duration	Not mentioned
Experimental Design	No pre-experimental designs
Significance	No statistical test done
Effects	
Physical	Acute tissue damage in the stranded and surface-floating giant squids (Injuries in the mantle tissues, damages in the circular and radial muscle fibres of the mantle, Damages in the internal organs (digestive organ,Stomach wall, Layers of columnar epithelium of branchial heart, Bruised gills and ovaries, statocysts damage.
Behavioral	Not studied
Physiological	

Table 15. Steffe and Murphy (1992)	
Where	Off Newcastle, Australia
When	August 1991
Species	*Penaeus plebejus*
Study Type	Monitoring (Pre- and post-seismic comparison of commercial trawl catches)
Sound Characteristics	
Source Type	Not mentioned
Source Levels	Not mentioned
Exposure Levels	Not mentioned
Exposure Duration	Not mentioned
Experimental Design	The seismic exploration could impact upon the king prawn catches during the survey period. (Depth of the fishing ground is not mentioned). Monitoring of the daily catch data for selected commercial fishermen (11 out of 288) between May and November 1991 (the seismic survey was conducted August 7 and 11 inclusive). The results were compared to the mean catch rates of the past six years from May to November.
Significance	No statistical test done
Effects	
Physical	Not mentioned
Behavioral	A declining trend in catches during the post-seismic survey period in 1991 is comparable to the catch rate reductions during the same period between 1985 and 1990. Any environmental impact must be large for it to be detected using fishery data alone. The authors were not be able to detect any impact on offshore prawn catches that could be due to the seismic survey, although it is possible that impacts may have occurred but could not be detected.
Physiological	Not studied

Table 16. La Bella et al. (1996)

Where	Central Adriatic Sea
When	Summer 1995
Species	*Nephrops norvegicus, Squilla mantis, Paphia aurea, Anadara inaequivalvis, Bolinus brandaris, Illex coindetti*
Study Type	Monitoring (pre- and post-seismic shooting catch comparison)
Sound Characteristics Source Type	One air gun array composed of two sub-arrays and consisting of 8 airguns each developing a total volume of c.a. 25000 in^3 at 2000 psi with an amplitude of 60 bar/m.
Source Levels	210 dB re 1μPa@1m*
Exposure Levels	≤ 147 dB re 1μPa@ fish location*
Exposure Duration	For Norway lobster and squid, 6 profiles totalling 111.3 km were covered by 10-12 hours of firing with 25 second intervals of shooting. at water depths of 70-75 m. For mantis shrimp and mollusks, 6 profiles totalling 42.82 km were covered by 3.9-4.6 hours of firing with 25 second intervals of shooting. at water depth of 15 m.
Experimental Design	Pre- and post catch rate comparisons by using trawl net (Norway lobster, squid), gillnets (Mantis shrimp) and hydraulic clam dredge (mollusks). Catch rates of crustaceans and mollusks are affected by seismic shooting. Two sub-arrays of 16 Bolt guns were towed at 5-6 knots at a depth of 6.5 m. Total of 8 trawl stations (4 in daytime, 4 in night) for Norway lobsters and squid, 14 stations for clam dredge for bivalves and gastropod, and two sets of gillnets (total 3200 m) for mantis shrimp, bivalves and gastropod were visited before and after the seismic testing. A comparative analysis of the hydrocortisone, glucose and lactate level was conducted in hepatopancreas and muscle of a bivalve *Paphia aurea* from seismic testing and control sites.
Significance	Pre- and post catch rates were compared by ANOVA test for Trawl (*N.n*, F=0.0004, *I.c*., F=0.234), Gill net (*S.m*., F=3.80, *B.b*., F=15.14,), and Dredge (*P.a.,* F=0.114, with vacant shell, F=1.822; *A.i*., F=0.549, *B.b*., F=2.216). Size frequency distributions were tested for *N. norvegicus* with Kolmogorov test males: D=0.048, χ^2=1.534, Females: D=0.071, χ^2=2.557) .
Effects	
Physical	No significant catch reductions and size difference in *N. norvegicus*.
Behavioral	No significant catch reduction in *I. coindetti*. No difference in *P. aurea, A. inaequivalvis* and *B. brandaris* caught by hydraulic dredge. Gillnet catch of *S. mantis* was not significantly different but *Bolinus brandaris* was significantly different before and after the seismic survey (F=15.14) by gill net.
Physiological	Hydrocortisone, glucose and lactate levels between test and control animals were significantly different (P > 0.05) in bivalve (*P. aurea*) showing an evidence of stress caused by acoustic noise.

4.2 Summary by authors/species/study type/results

Table 17. Explosives

Author	Year	Type	Category	Design	Source	Expo.	Species	Study	Table
Gowanloch & McDougall	1944	Exp.	Gray	No	No	No	White shrimp, Oyster	M	1
Aplin	1947	Exp.	Refereed	No	No	No	Abalone, Spiny lobster	M	2
Anonymous	1948	Exp.	Gray	No	Yes	No	Oyster, Blue crab	M	3
Sieling	1951	Exp.	Gray	No	No	No	Oyster	M	4
Kemp	1956	Exp.	Gray	No	No	No	White shrimp, Blue crab, Oyster	M	5
Anonymous	1962	Exp.	Gray	Yes*	No	No	Dungeness crab	M	6
Linton et al.	1985	Exp.	Gray	Yes	No	No	White shrimp, Blue crab, Oyster	M	7

Year: year of publication; Type: type of study (Exp: experimental, PSO: post-seismic observations); Category, Category of publication; Design, Design of study with enough number of samples, control and appropriate analyses of data?; Sound source and level specified?; Expo: Level of exposure to animals specified?; Species: Species name; Study: Study of type of effects: M, mortality, B, behavioral changes, P, Physiological changes; C: pre- and post-catch rate changes.

* Small sample size

4.2 Summary by authors/species/study type/results (continued)

Table 18. Summary of seismic air-guns study by species and type

Author	Year	Type	Category	Species	Study	Table
Norris and MØhl	1983	Exp.	Refereed	*Alloteuthis subrata* *Loligo vulgaris*	M, B M, B	8
Kosheleva	1992	Exp.	Gray	*Mytilus edulis* *Gammarus locusta*	M M	9
Matishov	1992	Exp.	Gray	Seaurchins *Chlamys islandicus*	M M	10
Webb and Kempf	1998	Exp.	Gray	*Crangon crangon*	M, C	11
McCauley et al.	2000a	Exp.	Gray	*Sepioteuthis australis*	B	12
Christian et al.	2003	Exp.	Gray	*Chionecetes opilio*	M, B, C_{Tr}	13
Steffe and Murphy	1992	CRA	Gray	*Penaeus plebejus*	C	14
La Bella et al.	1996	Exp.	Gray	*Nephrops norvegicus* *Illex coindetti* *Squilla mantis* *Paphia aurea,* *Anadara inaequivalvis* *Bolinus brandaris*	C_T, S C_T C_G C_D C_D C_D, C_G	15
Guerra et al.	2004	Obs.	Gray	*Architeuthis dux*	M, B	16

Exp.: Experimental; CRA: Catch rate comparison from logbooks; Obs.: Observations; M: Immediate mortality or other impact; B: Behavioral impact; C: Catch rate change; C_T: Trawl catch rate; S: Size frequency distribution; C_G: Gill net catch rate; C_D: Hydraulic clam dredge;
CTr: Trap catch rate

4.2 Summary by authors/species/study type/results (continued)

Table 19. Summary by species and effects of seismic air-guns with related information

Species	Source	Received	Distance (m)	Control	Effects	Sample
Alloteuthis sublata	Up to 260	Not mentioned	Not mentioned	No	Short-term tolerance	17
Loligo vulagrais	Up to 260	Not mentioned	Not mentioned	No	Died within 3-11 minutes	5
*Mytilus edulis**[1]	220-240 *[2]	- 220 *[2]	0.5, 1, 2	No	No apparent impact seen	-
*Gammarus locusta**[1]	220-240 *[2]	- 220 *[2]	0.5, 1, 2	No	No apparent impact seen	-
Chlamys islandicus	223 dB*[3]	217 *[3]	2	No	The shell split (1/3)	3
Seaurchins	223 dB*[3]	217 *[3]	2	No	15% of spine fell off	-
Crangon crangon	230-250	190	2 <	No	No mortality No reduced catch	-
Sepioteuthis australis	20 inc^3 with a gas pressure of 10-11 MPa (1500-1600 psi)	Up to 155 145-150 163	Approach-Departure variab. distance: farest 350-450, closest 5-15	Pre vs post	Increased swimming speed Increasing proportion of startle response Strong startle response (but not observed for similar or greater levels if signal ramped up)	14pre vs 14post
Chionoecetes opilio	197-237	201-227	2, 10, 15 *[4] 4, 50,85,170 *[5]	Yes	No immediate death (more energetic in some cases)	92T vs 92C
eggs				Yes	No physiological effect	variable (see table 13)
	221	216	2	Yes	Egg development may be delayed	1T vs 1C
		201	50	Pre vs Post	No observable reaction	30 min pre vs post
				Pre vs Post	Tr: No difference in catch rates.	variable (see table 13)
Penaeus plebejus	Not mentioned	Not mentioned	Not mentioned	Yes	Impact could not be detected	11 fishermen
Nephrops norvegicus	210 dB*[6]	<147 dB*[6]	70-75	Post vs pre	B: No difference in size frequency distributions and in catch rate	8T vs 8C
Illex coindetti	210 dB*[6]	<147 dB*[6]	70-75	Post vs pre	B: No difference in catch rate	8T vs 8C
Squilla mantis	210 dB*[6]	<147 dB*[6]	15	Post vs pre	G: No difference in catch rate	2T vs 2C
Architeuthis dux	Not mentioned	Not mentioned	Not mentioned	No	Standing and surface floting	9 observations
Paphia aurea	210 dB*[6]	<147 dB*[6]	15	Post vs pre	D: No difference in catch rate P: Significant	14T vs 14C Not mentioned
Anadara inaequivalvis	210 dB*[6]	<147 dB*[6]	15	Post vs pre	D: No difference in catch rate	14T vs 14C
Bolinus brandaris	210 dB*[6]	<147 dB*[6]	15	Post vs pre	D: No difference in catch rate G: No difference in catch rate	14T vs 14C 2T vs 2C

*[1] : Dalen (1994): *[2] :Turnpenny and Nedwell (1994); *[3] : Anonymous (2002); *[4] : a single 40-in^3 gun; *[5]: An array of 200-in^3 gun; *[6]: Hirst and Rodhouse (2000)
B: Bottom trawl; G: Gill net; D: Hydraulic clam dredge; Tr: Traps; P: Physiological examinations; T: Test; C: Control; Post vs pre: Post and pre-seismic comparison

5. References

5.1 Effects of seismographic explosions on invertebrates (*documents summarized in table)

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5.2 Effect of seismic guns on invertebrates (*documents summarized in table)

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