Chapter 3
Peer-Reviewed Studies on the Effects of Anthropogenic Noise on Marine Invertebrates: From Scallop Larvae to Giant Squid

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Abstract Marine invertebrates at the base of oceanic trophic webs play important ecological and economical roles supporting worldwide fisheries worth millions. There is an increasing concern about the effects of anthropogenic noise on marine fauna but little is known about its effects on invertebrates. Here the current peer-reviewed literature on this subject is reviewed, dealing with different ontogenetic stages and taxa. These studies show that the noise effects on marine invertebrates range from apparently null to behavioral/physiological responses to mortalities. They emphasize the need to consider potential interactions of human activities using intense sound sources with the conservation and fisheries of local invertebrate stocks.

Keywords Underwater noise • Seismic exploration • Shipping • Larval development

1 Introduction

Despite the global economic and ecological importance of invertebrates (Anderson et al. 2011), there are very few peer-reviewed papers investigating how they may be impacted by anthropogenic noise (Morley et al. 2014). This is in contrast to a growing literature about the effects of noise on fish (e.g., Popper and Hastings 2009). Most studies on the effects of noise on marine invertebrates are

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reported as industry or government reports, and these are commonly cited in the absence of appropriate peer-reviewed references. It is important to submit these reports to the peer-review process to make them generally available in the common scientific literature. They deal most often with the effects of seismic sounds on invertebrates, which have been studied more than the effects of other intense noise sources such as shipping, pile driving, or underwater explosions. The scarcity of peer-reviewed literature reporting experimental studies about the effects of underwater anthropogenic noise contrast with the widespread social concern about the effects of seismic and other human noise sources on fisheries. Despite uncertainties about how underwater noise may affect marine fauna, several countries have already implemented regulations that reduce the overlap between seismic surveys and fishing activities. These regulations increase the cost of exploration and so have important economic consequences. However, the absence of regulations could also be costly if the claimed harm is occurring.

Assessing the potential for sound to impact invertebrate fauna is complicated by the widely different responses at the behavioral and physiological levels that are expected from different species belonging to the large number of phyla of marine invertebrates. Moreover, ontogenetic stages from egg to larvae and adult forms may be impacted in different ways. Thus, a conservative approach must be applied when generalizing the results about the effects or apparent lack of noise impacts recorded in studies on a given taxa or ontogenetic stage, using a particular method. Some of the basic concepts that should be considered when investigating and reporting the effects of noise and when applying these results to design mitigation measures for anthropogenic noise sources are discussed here.

(1) Animals may not be able to escape. It is often expected that animals will avoid disturbing noise sources. However, many species are territorial or become territorial at certain times of the year, e.g., when guarding nests, whereas other species have limited movement capabilities. Both cases apply to many invertebrate taxa. Animals may interpret sound as a predator stimulus and respond to it with immobility. This is a typical response to predation threat (Brown and Smith 1998), probably to avoid indicating their presence with hydrodynamic cues. Also, animals may have restricted movements if they are dazed or disoriented by the sound exposure. For example, Solé et al. (2012) reported that cephalopods showed a light startle response before remaining motionless at the bottom of the tank during the rest of the exposition and after it (none ate any more mated, or laid eggs) until they were killed up to 96 h later; Fewtrell and McCauley (2012) also reported changes in swimming behavior and immobility in squids exposed to seismic sounds.
(2) The conclusions must be scientifically correct and fit the power of the experimental protocol. Studies target discrete questions and their conclusions should not be overinterpreted. For example, evaluations of fishing catch rates before and after noise exposure may show stable or even increased captures. This is a valid result for the fishery, but it does not provide any conclusions about the impact on the individuals or the stock. Behavioral responses of sound-exposed

animals, such as immobility, may be neutral to or favor capture by fishing methods such as trawling. However, acoustic damage to the individuals cannot be ruled out unless this is properly tested. Another example of the importance of restricting conclusions to the concrete analysis performed is that tissue/cellular damage is not homogeneous. Thus, analysis of the impact in some tissues may reveal no damage, whereas serious injury may have occurred in other body areas. André et al. (2011) and Solé et al. (2012) reported that no pathologies were found in any tissues of cephalopods exposed to noise except in their statocyst system, which were reported as incompatible with survival.

(3) Survival in the laboratory is not comparable to survival in the wild. Monitoring of animal survival in the laboratory implies controlled experimental conditions where animals are fed and protected from predators. This is an important source of bias because controlled conditions provide a sheltered environment where animals suffering recoverable behavioral or physiological damages may survive. In a natural environment, debilitated individuals are subject to higher predation risk and may have reduced foraging success, limiting their survival in the wild.

2 Summary of Peer-Reviewed Papers on the Effects of Noise on Invertebrates

Findings of the papers dealing with the effects of anthropogenic noise in different phyla of invertebrates that have been published in peer-reviewed journals are summarized here. A schematic view is provided in Table 3.1.

2.1 Aguilar de Soto et al. (2014) Scientific Reports

This paper provides the first evidence that noise exposure during development can produce body malformations in larvae of marine invertebrates. New Zealand scallop larvae exposed to playbacks of seismic pulses in the laboratory showed significant developmental delays and 46% developed body abnormalities. Similar effects were observed in all independent samples exposed to noise, whereas no malformations were found in the control groups (4,881 larvae were examined). Malformations appeared in the D-veliger larval phase, perhaps due to the cumulative exposure attained by this stage or to a greater vulnerability of the D-veliger phase to sound-mediated physiological or mechanical stress. Such strong impacts suggest that abnormalities and growth delays may also result from lower sound levels or discrete exposures during the D-stage, increasing the potential for routinely occurring anthropogenic noise sources to affect the recruitment of wild scallop larvae in natural stocks. The exposure consisted of the playback in a large tank of a seismic pulse

Table 3.1 Results of peer-reviewed literature on noise-impact studies in invertebrates

Reference	Species	Summary results	Total duration	Levels	Frequency	Noise exposure
Aguilar de Soto et al. (2013)	Scallop larvae	Significant delay in development and 46% of larvae with malformations	90 h of pulses every 3 s	SEL pulse 163 dB rms re 1 μPa^2·s at 3–4 ms^{-2}	−3 dB band at 89–129 Hz	Tank playback of prerecorded seismic array
André et al. (2011). See Solé et al. (2012) for details and additional results						
Andriguetto-Filho et al. (2005)	Three species of shrimps	No decrease in trawling catch rates nor shrimp density	1 day of air gun pulses, each 12 s	Peak source level of 196 dB re 1 μPa at 1 m	Not measured	Field Four air gun seismic array
Branscomb and Rittschof (1984)	Barnacle larvae	Lower settlement in cyprid larvae up to 13 days old	20 h or more	Not reported	30 Hz 20–40 Hz	Laboratory Hull Tender
Fewtrell and McCauley (2012)	Squid	Startle responses and behavioral changes increasing with sound level	Air gun passes ≤1 h long Pulse rate 10 s	136 to >162 dB re 1 μPa^2·s	−10 dB band at ≈ 20–70 Hz	Field One seismic air gun
Guerra et al. (2011)	Giant squid	Two atypical mass strandings. Damages to tissues and statocysts	Seismic survey	Ten air gun seismic array	Seismic pulses	Field Air gun array
Kight and Swaddle (2011)	Varied	Excellent review of mechanistic effects of noise at physiological and cellular level	Varied	Varied	Varied	Many

Lagardère (1982)	Shrimp	Reduced growth, feeding and reproductive rates	Compared usual ambient in rearing tanks against soundproof conditions 30 dB lower. Responses started after a few hours and did not decrease in 5 days of experiment			Tank playback
Lagardère and Régnault (1980)		Increased metabolic rate (O_2 intake and ammonia excretion)				
Regnault and Lagardère (1983)		Reduced growth and weight gain				
Parry and Gason (2006)	Rock lobster	No decrease of fishing captures observed	Several seismic surveys in Western Australia (statistical analysis of catch rate in fishing records)			Field Seismic arrays
Pearson et al. (1994)	Crab larvae	Tank following after field exposure showed no increase in mortality nor time to molt between larvae exposed to 1 seismic pulse and the control group	One seismic pulse	231 dB re 1 μPa	–	Field/tank Seismic array of seven air guns
			All larvae (including control) exposed to elevated ambient noise in the field of 156–168 dB re 1 μPa			
Solé et al. (2012)	Cuttlefish, squid	Strong damages to statocyst system	2 h 1-s sweep period	Median/peak RL: 157/175 dB re 1 μPa	50–400-Hz sweep	Tank low-frequency sweeps
Wale et al. (2013a)	Shore crabs	Size-dependent increase in oxygen consumption	Single/repeated playback of 7 min	148–155 dB re 1 μPa rms	–10 dB bandwidth <2.4 kHz or <300 Hz	Tank playback Ship noise
Wale et al. (2013b)	Shore crabs	Effects on feeding behavior. Unrighted noise-exposed crabs turned over faster and retreated to shelter slower.				

SEL sound exposure level, *rms* root-mean-square recorded at tens of kilometers from a seismic survey vessel (details in Table 3.1). The noise-exposed and control groups were several independent flasks with eggs from the same egg mix. The flasks were located in a tank with a J9 transducer emitting the playback while the control flasks were located at the same time in an adjacent tank with same conditions except for the playback.

2.2 André et al. (2011) Frontiers in Ecology and the Environment and Solé et al. (2012) Deep-Sea Research Part II-Topical Studies in Oceanography

These papers present results showing the first morphological and ultrastructural evidence of massive acoustic trauma in four cephalopod species (*Sepia officinalis*, *Octopus vulgaris*, *Loligo vulgaris*, and *Illex condietii*) subjected to low-frequency playbacks of a 50–400-Hz 1-s sweep for 2 h from an air speaker. The authors reported a received level of 157 dB re 1 μPa in the tank holding the animals, with peak levels up to 175 dB re 1 μPa. Exposure to low-frequency sounds resulted in permanent and substantial alterations of the sensory hair cells of the statocysts, the structures responsible for the animals' sense of balance and position. The analysis was performed using scanning (SEM) and transmission (TEM) electron microscope techniques of the whole inner structure of the cephalopods' statocyst, especially on the macula and crista. All exposed individuals presented the same lesions and the same incremental effects over time, which were absent in control individuals that had been exposed to the same treatments except for the noise playback.

Lesions were evident in animals killed from 0 to 96 h after exposure, with no clear evidence of recovery, although the authors observed scarring processes in some specimens at 48 h. In contrast, the most important lesions on the macula and crista epithelia were observed on the specimens killed 96 h after exposure. The authors discussed that this degenerative process may be due to the cytotoxic effect of glutamate, which usually works as a neurotransmitter but can be released in excess as a response to stressful loud noise, leading to neuronal and sensorial epithelium damage.

2.3 Andriguetto-Filho et al. (2005) Continental Shelf Research

The authors reported on the first study to explicitly assess the impact of seismic prospecting on shrimp resources. They measured bottom trawl yields of a nonselective commercial shrimp fishery comprising the Southern white shrimp *Litopenaeus schmitti*, the Southern brown shrimp *Farfantepenaeus subtilis*, and the Atlantic seabob *Xyphopenaeus kroyeri* (Decapoda, Penaeidae) before and after the use of an array of four synchronized air guns (Table 3.1). Their results did not detect significant decreases in the catch rates of the trawls nor in the density of the species in the area within a day after the seismic exposure was finished.

2.4 Branscomb and Rittschof (1984) Journal of Experimental Marine Biology and Ecology

Inhibition of barnacle settlement was achieved using low-frequency (30-Hz) sound waves on laboratory-reared larvae of *Balanus amphitrite*. Less than 1% of very young cyprid larvae (0 days old) settled in the presence of the sound waves. Cyprids caught in plankton tows responded very similar to laboratory-reared larvae. Although the percentage of settlement tends to increase with older larvae, low-frequency sound reduced the percentage of metamorphosis for cyprids up to 13 days old. The exposure was performed with an nondescribed commercially available device, the Hydro-Sonic Hull Tender (Scientific Technologies, Aiken, SC).

2.5 Fewtrell and McCauley (2012) Marine Pollution Bulletin

In this experiment, squid in large cages in the field were exposed to passes in the 5–800-m range of a single air gun (source level at 1 m of 192 dB re 1 $\mu Pa^2 \cdot s$) shooting every 10 s. Squid showed startling responses and behavioral responses from the minimum received levels (RLs) and increased with the increasing RL. RLs ranged from 136 to >162 dB re 1 $\mu Pa^2 \cdot s$. Behavioral changes included changes in swimming behavior and vertical location in the cage and reduced movement.

2.6 Guerra et al. (2011) Biological Conservation

These authors associated two geophysical seismic surveys to two atypical mass strandings of giant squid (*Architeuthis dux*), with some squid showing extensive tissue damage. Long-term records of strandings of giant squid in the area (Asturias, northern coast of Spain) do not exceed one or two animals per year except in autumn 2001 and September 2003. In these two cases, five and four animals, respectively, were found stranding or floating for short time periods and in localized areas. These cases resulted in a significant increase in the probability of giant squid strandings in the area. The specimens in the mass strandings ranged from 60 to 200 kg in weight and 7–12 m in total length. They showed no obvious external cause of death, but internal examinations showed that two of the squid suffered extensive damage to internal muscle fibers; their stomachs were ripped open and their digestive tracts were mangled. The squid also suffered severe damage to their statocysts, the structures responsible for the animals' sense of balance and position. The authors proposed that this disorientation may be the cause of death of the squid without clear organic damage if these moderately active, buoyant giant squid floated toward the surface where they died. Moving from deep cold waters to warmer and shallower waters causes oxygen desaturation given the low affinity to oxygen at a high temperature of their oxygen carrier protein hemocyanin.

2.7 Lagardère (1982) Marine Biology and Regnault and Lagardère (1983) Marine Ecology Progress Series

The team of Regnault and Lagardére produced several papers reporting that a continuous raised ambient noise in aquariums of ~30 dB at 25–400 Hz increased metabolism (higher oxygen consumption and ammonia excretion) and reduced growth and reproductive rates in brown shrimp (*Crangon crangon*). The increases in metabolic rate were expressed within a few hours, and there was no evidence of habituation during the experiment (5 days). The authors interpreted the observed increases in cannibalism and mortality rates and decreased food uptake to be signs of stress.

2.8 Parry and Gason (2006) Fisheries Research

The effect of seismic discharges on rock lobsters was investigated through statistical analysis of the coincidence between seismic surveys and changes in commercial catch rates in western Victoria between 1978 and 2004. In 12 depth-stratified regions, the number of acoustic pulses during seismic surveys was correlated with the catch per unit effort (CPUE) of rock lobsters to determine whether catch rates were affected in the years after seismic surveys. In three regions subjected to intensive seismic surveys, two-way analysis of variance was used to detect short-term (weekly) changes in the CPUE before, during, and after these seismic surveys. There was no evidence that the catch rates of rock lobsters were affected by seismic surveys in the weeks or years after the surveys. The authors discussed these results in the context of most seismic surveys occurring in deep water where impacts would be expected to be minimal.

2.9 Pearson et al. (1994) Marine Environmental Research

Larvae reared in the laboratory were transported to the field where they were exposed to one pulse from a seven air gun array or to a mock exposure without the array actually shooting (control group). Ambient-sound levels measured during the control periods of the experiment were abnormally high due to the compressor of the air gun array and varied from 156 to 168 dB re 1 μPa. Larvae were then transported back to the laboratory for monitoring in controlled conditions. Larvae exposed to the seismic pulse did not show differences in the survival rate and the time to molt compared with the control group.

2.10 Wale et al. (2013a) *Biology Letters* and Wale et al. (2013b) *Animal Behaviour*

The authors used controlled experiments to investigate in the laboratory how the physiology and behavior of the shore crab (*Carcinus maenas*) is affected by both single and repeated exposure to ship-noise playback. Crabs experiencing ship-noise playback consumed more oxygen, indicating a higher metabolic rate and potentially greater stress, than those exposed to ambient-noise playback. The response to single-ship noise playback was size dependent, with the heavier crabs showing a stronger response than lighter individuals. Also, the authors observed subtle changes in the feeding behavior of the crabs and differences in the time to retreat to shelter and time to turn to recover a right position, suggesting that noise-exposure may affect predator responses in the wild.

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