Review of the effects of underwater sound, vibration and electromagnetic fields on crustaceans

May 2020

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This report should be cited as:
Scott, K., Piper, A.J.R. Chapman, E.C.N. & Rochas, C.M.V., 2020. Review of the effects of underwater sound, vibration and electromagnetic fields on crustaceans. Seafish Report.

This report was prepared under contract by

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Summary

This report was written to support the UK seafood industry when engaging with offshore development proposals that may result in anthropogenic sound, seabed substrate-borne vibration, and Electromagnetic Fields (EMFs).

Table 1 provides an overview of the existing literature concerning the effects of these stressors on crustacean species across the world. Most of this work does not cover species of commercial significance in the UK. A key point to note is that most of these studies used sources mimicking the stressor type, rather than exposing individuals to the actual stressor (e.g. boat noise).

Table 1. Executive summary of effects of underwater noise, vibration, and electromagnetic fields (EMF) on crustaceans.

Stressor	Metric	Effect	References
Anti-fouling device / seismic survey / tidal and wind turbine running noise	Egg, larval or embryonic development	Mixed - effects sometimes seen	Branscomb & Rittschof 1984[1], Day et al. 2016[2], DFO 2004[3], Pearson et al. 1994[4], Pine et al. 2012[5]
Artificial (anthropogenic) noise / ship noise	Hermit crab shell selection, decision making, and grouping behaviours	Mixed responses	Tidau & Briffa 2019[6], Tidau & Briffa 2019[7], Walsh et al. 2017[8]
Artificial (anthropogenic) noise / pile driving noise	Acoustic behaviour (making noise)	Increased	Filiciotto et al. 2018[9], Spiga 2016[10]
Artificial (anthropogenic) noise / pile driving noise/ seismic survey / ship noise	Biochemistry or organ histology	Mixed - effects sometimes seen	Celi et al. 2015[11], Christian et al. 2003[12], Day et al. 2019[13], DFO 2004[3], Filiciotto et al. 2014[14], Filiciotto et al. 2016[15], Filiciotto et al. 2018[9], Fitzgibbon et al. 2017[16], Payne et al. 2007[17], Solan et al. 2016[18]
Artificial (anthropogenic) noise / pile driving noise / seismic survey / ship noise	Movement	Mixed responses	Filiciotto et al. 2014[14], Filiciotto et al. 2016[15], Filiciotto et al. 2018[9], Solan et al. 2016[18], Zhou et al. 2016[19], Zhou et al. 2018[20]
Artificial (anthropogenic) noise / seismic survey / ship noise	Feeding/foraging behaviours	Mixed - effects sometimes seen	DFO 2004[3], Hubert et al. 2018[21], Payne et al. 2007[17], Wale et al. 2013[22]
Aquarium noise	Growth and reproduction rates	Changed	Lagardère 1982[23]
Aquarium noise / ship noise	Metabolism	Changed	Regnault & Lagardère 1983[24], Wale et al. 2013[25]

Stressor	Metric	Effect	References
Offshore construction / pile driving / ship noise	Gene expression	Changed	Celi et al. 2015[11], Filiciotto et al. 2014[14], Filiciotto et al. 2016[15], Zhou et al. 2018[20]
Offshore construction / ship noise	Burying and bioirrigation behaviours	Changed	Solan et al. 2016[18]
Seismic survey	Catch rates/trawl yields	None	Andriguetto-Filho et al. 2005[26], Christian et al. 2003[12], Morris et al. 2018[27], Parry & Gason 2006[28]
Seismic survey	Mortality	None	Christian et al. 2003[12], DFO 2004[3], Morris et al. 2018[27], Payne et al. 2007[17]
Seismic survey	Fecundity	None	Day et al. 2016[2]
Seismic survey / ship noise	Damage to mechanosensory organs, effect on righting reflex	Mixed - effects sometimes seen	Day et al. 2019[13], DFO 2004[3], Wale et al. 2013[22]
Seismic survey / ship noise / substrate-borne vibration	Anti-predator response or vigilance	Mixed responses	Chan et al. 2010[29], Day et al. 2019[13], Nousek-McGregor & Mei 2016[30], Roberts & Breithaupt 2016[31], Wale et al. 2013[22]
Ship noise	Avoidance behaviour	None	Brierley et al. 2003[32]
Ship noise	Time outside shelter	Increased	Filiciotto et al. 2016[15]
Substrate-borne vibration	Attraction to chemical cue	Reduced	Roberts & Laidre 2019[33]
Substrate-borne vibration	Behaviours indicating whether organism has detected a stimulus	Changed	Roberts et al. 2016[34], Roberts & Breithaupt 2016[31]
EMF	Movement	Changed	Ernst & Lohmann 2016[35], Lohmann et al. 1995[36], Rosaria & Martin, 2010[37], Scott et al. 2018[38], Tański et al. 2005[39], Ugolini 2001[40], Ugolini, 2006[41], Ugolini & Pezzani 1995[42], Woodruff et al. 2012[43], Ye et al. 2004[44], Yeh et al. 2008[45]
EMF	Aggression	Increased	Rosaria & Martin 2010[37]
EMF	Physiological	Changed	Lee & Weis 1980[46], Rosaria & Martin 2010[37], Scott et al. 2018[38], Shckorbatov et al. 2010[47], Uzdensky & Kuyko 1997[48], Ye et al. 2004[44], Yeh et al. 2008[45]
EMF	Egg hatching success	Increased	Shckorbatov 2010[47]

Key points:

- This literature review highlights the lack of knowledge on the effects of noise, vibration, and EMFs on crustaceans. Limited research with mixed results precludes the ability to draw overall conclusions, but highlights the potential for these stressors to have an influence on crustaceans in general and the necessity of future research to identify vulnerable species and life stages.
- Noise studies on UK commercially important crustaceans are very limited. Robust knowledge of known sensitivities to noise and vibration have not been documented, nor have behavioural and physiological changes at different parts of the life cycle. However, the ecosystem engineering behaviours and bioirrigation of the Norway lobster (*Nephrops norvegicus*) are influenced by shipping and construction noise. In addition, a PhD thesis noted alteration of different aspects of the Norway lobster's larval life cycle in response to shipping noise, which can lead to a reduction in predator avoidance stamina. Shipping noise was also suggested to elicit avoidance behaviour in the European lobster *(Homarus gammarus)* in another PhD thesis.
- Particle motion (the movement of particles around a sound wave to allow for its transmission) is the aspect of noise most likely detected by crustaceans. A modelling study suggested that particle motion can be detected on the seafloor up to 400 m from a pile driving site.
- Crustaceans have the ability to detect and utilise EMF with a relatively high degree of sensitivity. As a result, environmental fluctuations caused by Marine Renewable Energy Devices (MREDs) may have a multitude of effects on crustacean behaviour and physiology.
- Exposure to EMF has been shown to alter adult edible crab (*Cancer pagurus*) and European lobster physiology and larval development resulting in significantly smaller size individuals. Circadian rhythms were disrupted in both species, possibly due to increased anaerobic respiration and potentially the onset of hyperglycaemia - both known responses to stress - although longer term studies are required to confirm this. Edible crabs were affected behaviourally whereby attraction to EMF source potentially overrides natural foraging behaviours, whilst there have been mixed European lobster behaviour results. European lobsters have also shown an immune response to EMF exposure, as observed through a significant change in haemocyte levels.
- It is possible that crustaceans will be exposed to both noise and EMF simultaneously, or within short time periods, particularly surrounding windfarm and other MRED construction and operation. There are currently no research papers looking at the combined effects of noise, vibration, and EMF on crustaceans.

- Research limitations and mixed evidence of effects prevents any suggestions for whether crustacean specific mitigation is even required.
- Subsea power cable burial has been shown to reduce EMF strength at the surface of the seabed. The reduction in field strength is dependent on burial depth, original field strength emissions and cable shielding. This reduction in field strength may help alleviate the impacts of EMF exposure on crustaceans; however, further research is required.
- Some marine mammal noise mitigation methods may inadvertently benefit crustaceans, for example those that may reduce particle motion (e.g. hydraulic pile driving instead of impulsive pile driving); however, these have yet to be studied with respect to crustaceans.
- Future research needs to follow a standardised experimental design that evaluates particle motion and EMFs on UK commercially important species in the long term. There is a need to identify the most vulnerable species groups, distinguish spatial and temporal factors, and use a mechanistic, integrative approach. Influence on crustacean behaviour, physiology and, ultimately, commercial catchability needs to be comprehensively assessed so that appropriate mitigation methods can be recommended.

Contents

Glossary

Term	Definition
Acoustic pressure	A local change in pressure from the usual background pressure, created by a sound wave.
Additive effects model	Used when combined effects of multiple stressors are summed together to give an additive, synergistic, or antagonistic interaction effect and assumes a linear stressor-effect relationship
Additive interaction effect	Total level of the effects is equal to the sum of the individual effects
Amphipod	Member of the invertebrate order Amphipoda (class Crustacea), shrimp-like in form
Amplitude (of a sound wave)	The height of a sound wave. The higher the amplitude, the louder the sound.
Antagonistic interaction effect	Total effect is less than the sum of individual effects, i.e. less than the additive effect
Autotomised limb stump	The stump left after a limb was autotomised (self-amputation)
Bioirrigation	The process in which animals living in the seafloor flush out their burrows with the water over the top of them.
Body scanning behaviour	A behaviour used to determine the geomagnetic reference direction by scanning the horizontal component of the magnetic field by left and right oscillations of the entire major body axis
Decapod	Decapoda (‘ten-footed’) is an order of crustacean that includes shrimp, lobster, hermit crabs, crayfish, crabs
Endocrine	A term referring to all structures which produce hormones and other substances directly into the blood (or “haemolymph” in crustaceans) as opposed to target tissues
Frequency	The number of times a sound wave fully repeats itself in one second
Haemolymph	Crustacean “blood”
Hepatopancreas	An organ in crustaceans akin to a combination of a pancreas and liver
Heterotrophs	An organism that cannot produce its own food
Isopods	Member of the invertebrate order Isopoda (class Crustacea) that includes woodlice and their relatives

Magnetic symmetry plane	The predicted symmetry around the north-south or east-west magnetic axis
Masking (in terms of noise)	The process in which an additional, unusual sound in an environment covers the usual background noise and interrupts potentially important biological noises
Mechanosensory organs	Structures of a creature which aid in the detection and processing of “mechanical” stimuli, such as vibration, particle motion or pressure
Metamorphosis (in crustaceans)	The point in the life cycle in which crustacean larvae most dramatically change towards the final adult form.
Multiplicative effect model	Used to describe competitive interactions where one stressor can be further operated on probabilistically by another stressor, and the maximum effect cannot be greater than 100%
Particle motion	Sound waves cause alternating areas of higher and lower pressure in water as they propagate, which in turn causes the surrounding particles to move. The movement of these particles to allow for the movement of a sound wave is called particle motion, which is measured in terms of particle displacement, velocity or acceleration
Propagate	How far something is able to spread (e.g. the distance which underwater sound can be heard from the source)
Reception indicators	Behaviours used to observe whether an organism detects a certain stimulus
Righting reflex/time	A common behaviour to test in crustaceans involves placing them on their “backs”, and timing how long it takes them to flip themselves back over (i.e. correct or “right” their position in the water). This can be correlated to the functioning of related mechanosensory organs.
Settlement (in crustacean larvae)	Crustacean larvae exist as plankton (in the water column, away from the seabed) for the first stages in their life cycle. When they develop to a late enough stage, they move to the seafloor to grow and become adults.
Simple comparative effects model	Used when the resulting effect of multiple stressors is equal to a single dominant stressor
Sound exposure level	The energy given out by an acoustic source

Sound pressure level	The pressure level created by a sound wave, compared to a reference level
Stressor	A factor or condition which causes stress to an animal
Synergistic interaction effect	Total effect is greater than the sum of individual effects, i.e. greater than the additive effect
Total haemocyte count	The total number of haemocytes (a type of cell) in the haemolymph of a crustacean

Acronyms & units

A	Amps
AC	Alternating Current
ADD	Acoustic Deterrent Device
ATP	Adenosine Triphosphate
AUV	Autonomous Underwater Vehicle
B-Field	Magnetic Field
CBN	Continuous Broadband Noise
CO_2	Carbon dioxide
CPUE	Catch Per Unit Effort
dB	Decibel
DC	Direct Current
E-Field	Electric Field
EIA	Environmental Impact Assessment
EMF	Electromagnetic Field
ES	Environmental Statement
GHG	Greenhouse Gas
GW	Gigawatt
hr	Hour
HSP	Heat Shock Protein
HVDC	High Voltage Direct Current
Hz	Hertz
IBN	Impulsive Broadband Noise
iE-Field iEMF	Induced Electromagnetic Field
in	Inches
J/m^2	Joules per square metre
kHz	Kilohertz
km	Kilometre
kV	Kilovolt
kW	Kilowatt
L	Litre
lbs	Pound
m	Metre
MPa	Megapascal

MRE	Marine Renewable Energy
MRED	Marine Renewable Energy Device
msec	Millisecond
mT	Millitesla
MW	Megawatt
MWh	Megawatt hours
ORED	Offshore Renewable Energy Development
PCAD	Population Consequence of Acoustic Disturbance (model)
p-p	Peak-to-peak
psi	Pound per square inch
RMS	Root Mean Square
s	Second
SD	Standard Deviation
SEL	Sound Exposure Level
SPL	Sound Pressure Level
T	Tesla
THC	Total Haemocyte Count
TNT	Trinitrotoluene
TTM	Time To Metamorphosis
UXO	Unexploded Ordnance
V	Volt
WEC	Wave Energy Converters
µbar	Microbar
µPa	Micropascal
µT	Microtesla

1. Introduction

1.1. Offshore renewable energy devices

Anthropogenically induced (man-made) climate change from Greenhouse Gas (GHG) emissions has a significant evidence base and poses an existential threat to humanity (dubbed the “climate emergency”). This has led to many governments initiating programs for increased production of renewable or ‘green’ energy[49] to meet our energy demands, replacing reliance on burning fossil fuels. Offshore marine renewable energy (MRE) is seen by many governments as a vital part of meeting net zero carbon emission targets.

There are three prominent types of MRE: wave, tidal, and wind, with wind being the most common. Renewable energy structures are increasingly being located offshore due to:

- Onshore limitations
  - Planning restrictions
  - Lack of inexpensive land near population centres[50]
  - Aesthetic problems[51]
- Major potential offshore
  - Larger amounts of energy per turbine[50]
  - Significantly higher wind speeds
  - Less turbulent flow over the sea (i.e. production more efficient)
  - Vast open spaces to help avoid wake effects (shading effect of a turbine on those downwind of it)[52]

Currently, the UK is the largest global producer of electricity from offshore windfarms and has more projects in planning or construction than any other country worldwide[53]. The UK has agreed a target of net-zero GHG emission by 2050[54]. It is estimate that to meet this target 75 GW of energy per annum would need to be produced from offshore wind by 2050, compared to the 9.9 GW produced in 2019 and the 30 GW target of 2030[53–55]. At the end of 2019, there were 2,225 offshore wind turbines connected in the UK from 40 offshore wind farms[55] (Figure 1). The 75 GW target for 2050 may require up to 7,500 turbines[54].

The rapid increase in renewable energy in the relatively untapped marine environment[49] is not without its problems. There are social and environmental concerns[38,49,51,56–58] including:

- Habitat loss
- Collision risks
- Increased anthropogenic noise
- Exposure to increased Electromagnetic Fields (EMF)

Unfortunately, significant gaps exist in the current knowledge of the effects of renewables on marine and freshwater organisms[38,59,60].

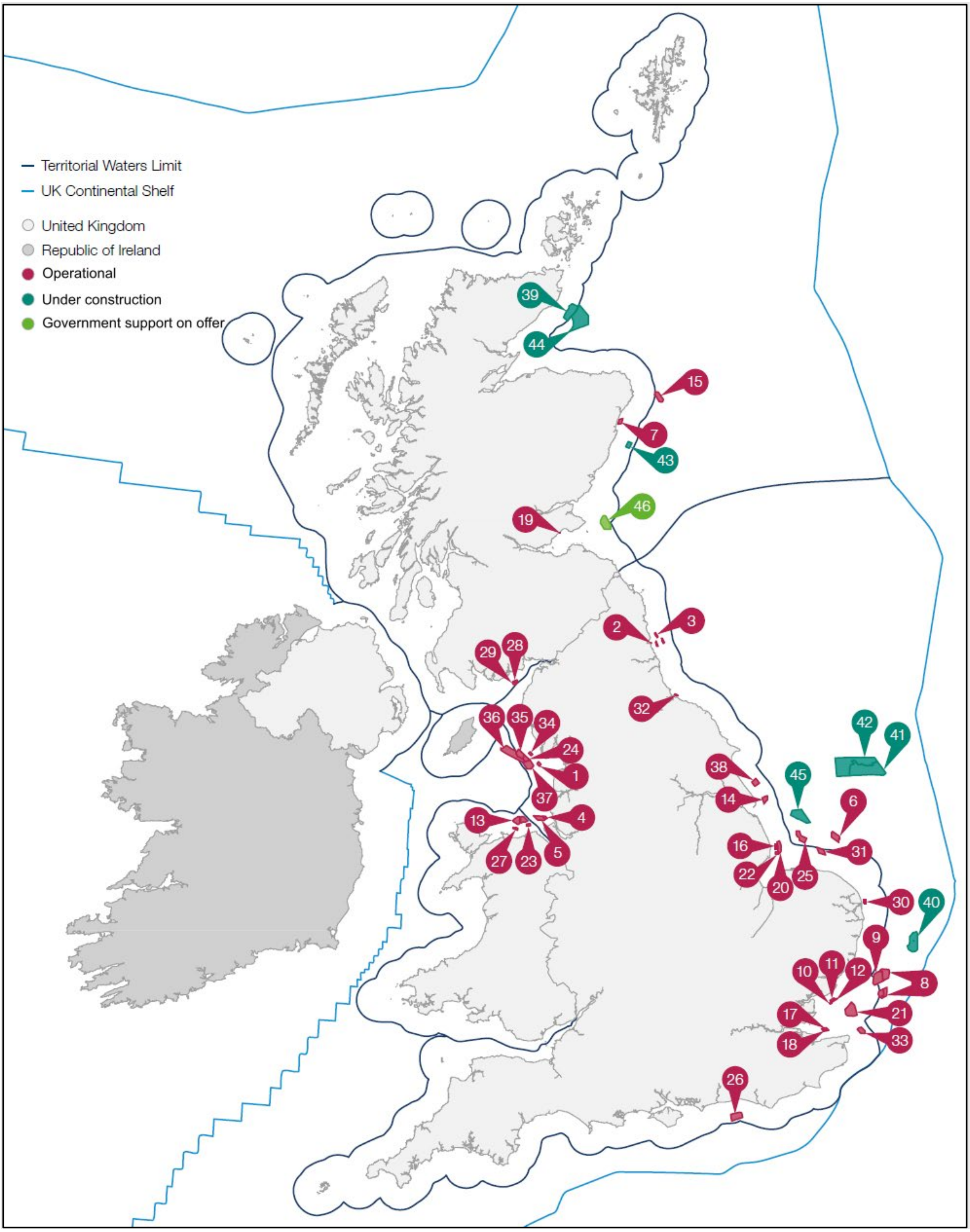

Figure 1. UK offshore wind project pipeline. Map from The Crown Estate 2018 report[53]. See report for full details on individual wind farms (numbers indicated on map) and their capacities (From www.thecrownestate.co.uk)

1.2. Underwater sound & vibration

All aspects of Marine Renewable Energy Devices (MREDs) will generate some degree of noise within the marine environment, which may have the potential to interfere with marine organisms[21]. Other sources of anthropogenic noise come from activities such as:

- Oil and gas exploration and subsequent extraction
- Construction (e.g. offshore structures, bridges, port developments)
- Vessel noise (e.g. commercial shipping, fishing vessels, recreational vessels)
- Military operations
- Seabed mapping (e.g. oil and gas exploration, scientific, pre-construction surveys)
- Acoustic Deterrent Devices (ADDs)

Table 4 in Appendix 1 (Further background material) summarises reported source levels of some common marine anthropogenic noises.

Research into the use of underwater acoustics by marine organisms historically revolved around marine mammals, showing that they use sound for a variety of functions (including communication, finding food, and avoiding threats[61–65]), followed by an effort to increase understanding in commercially important finfish species[66,67]. Due to the legal protection given to marine mammals[68] the potential effects of anthropogenic noise on this group of animals is highly regulated[69], which includes licencing requirements for MREDs, and has therefore been a large driver for funding and research in this area. Despite the fact that invertebrates are incredibly numerous, accounting for a large proportion of marine biomass[21], and of vital ecological importance (e.g. as a lower trophic level food source or as ecosystem engineers[18]), we know very little about their use and detection of noise or how anthropogenic noise influences them[18,67]. It has been suggested that invertebrates may use noise to direct larval settlement once they leave their planktonic stages, avoid predators, find prey, and for orientation[66,67,70]. Currently, how crustaceans may use and detect noise is poorly understood[5,21], but some studies have hypothesised that crustaceans may use noise for purposes including communication, anti-predation and warning measures, stunning prey, and defending territories[9,71,72].

Research to date has ascertained sensitivities of crustaceans to sound (Table 5 in Appendix 1) and vibration (Table 6 in Appendix 1), both relative to the frequency of noise; however, owing to research limitations (discussed in Section 4), these cannot be taken as conclusive detection limits, but rather provide examples representative of current literature. While some of the sensitivities in terms of frequency appear at first glance to cross-over with the frequency ranges reported from various anthropogenic sources (Table 4 in Appendix 1), the significance of this, and whether said activities may have an impact on crustaceans, is currently unknown. For more details on different components and measures of sound, and the tables mentioned, see Appendix 1.

When sound is made it causes surrounding particles to move and transmit their movements to their neighbours. The movement of these particles to allow for the transmission of a sound wave is called particle motion, which is measured in terms of particle displacement, velocity, or acceleration[72,73]. The movement of particles causes areas of low and high pressure within the medium (Appendix 1 – Further background material, Figure 10). Higher levels of pressure, measured as Sound Pressure Level (SPL), are perceived as louder sounds. Crustaceans are more likely to be sensitive to particle motion as they do not have any gas-filled cavities or organs which would be affected by pressure[67]. The mechanisms of how crustaceans detect particle motion are unclear, but it is currently understood to involve the detection of surrounding water and sediment disturbances by mechanosensory organs[70]. These organs are located in various parts of the crustacean body, including the antennae and legs[67]. One of these organs, the statocyst, contains sensory hairs and structures called statoliths, and are thought to be associated with helping crustaceans maintain balance and orient themselves in the water[73,74].

1.3. Electromagnetic fields

MREDs are currently connected via subsea power cables, inter-turbine cables, cables to power storage banks, and export cables from deployment sites to shore (Figure 2). Subsea power cables carry electric currents via Alternating Current (AC) or Direct Current (DC) depending on transmission distance, capacity, and cost. DC cables can transmit more power than an AC cable of comparable size and over greater distances with less power loss, but with higher associated costs[75]. As such, AC cables tend to be utilised more often within MRED grids, with High Voltage Direct Current (HVDC) used to export from deployment to shore. For more background on EMF around subsea cables see Appendix 1.

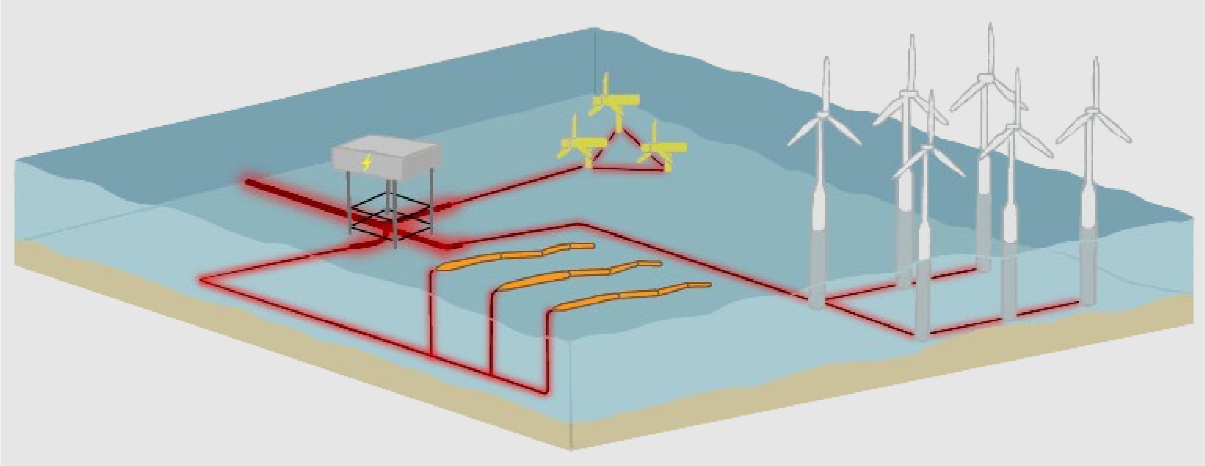

Figure 2. Illustration of subsea cables around Marine Renewable Energy Devices (MREDs). © St Abbs Marine Station.

The number of subsea cables on the seafloor worldwide has grown exponentially, with approximately 10^6 km of cables (including telecommunication and AC and DC power cables) currently occupying the seafloor[75,76]. As of 2015, 8,000 km of HVDC cables had been deployed on the seabed worldwide with almost 70% contained within European waters[75] (Figure 3).

EMFs not only originate from anthropogenic sources (telecommunication cables, power cables, marine renewable energy devices), but also natural sources, i.e. the Earth's natural geomagnetic field. Although many species (including crustaceans) use the Earth's geomagnetic field, primarily for navigation, the mechanisms underpinning EMF detection are unknown. Results obtained from studies that have investigated the role of the antennules, the primary chemosensory organ and crucial part of the crustacean olfactory system, were inconclusive, although appeared to confirm that antennules did not play a significant role in EMF detection[38,43]. More recent studies have focussed on two primary mechanisms for animal EMF detection: chemically mediated magnetoreception[77,78] and magnetite magnetoreception[35,79–81]. Magnetite (Fe_3O_4), a mineral found in the tissues of many animals[82–84] (including crustaceans[35]), is thought to react with magnetic fields and, through reorientation, acts upon secondary receptors[81,85]. A study conducted by Ernst and Lohmann[35] highlighted that a short magnetic pulse affected the orientation of Caribbean spiny lobsters (*Palinurus argus*), a change that is not thought to occur in chemically induced magnetoreception[86], suggesting magnetite crystals may be the prominent means of EMF detection in crustaceans.

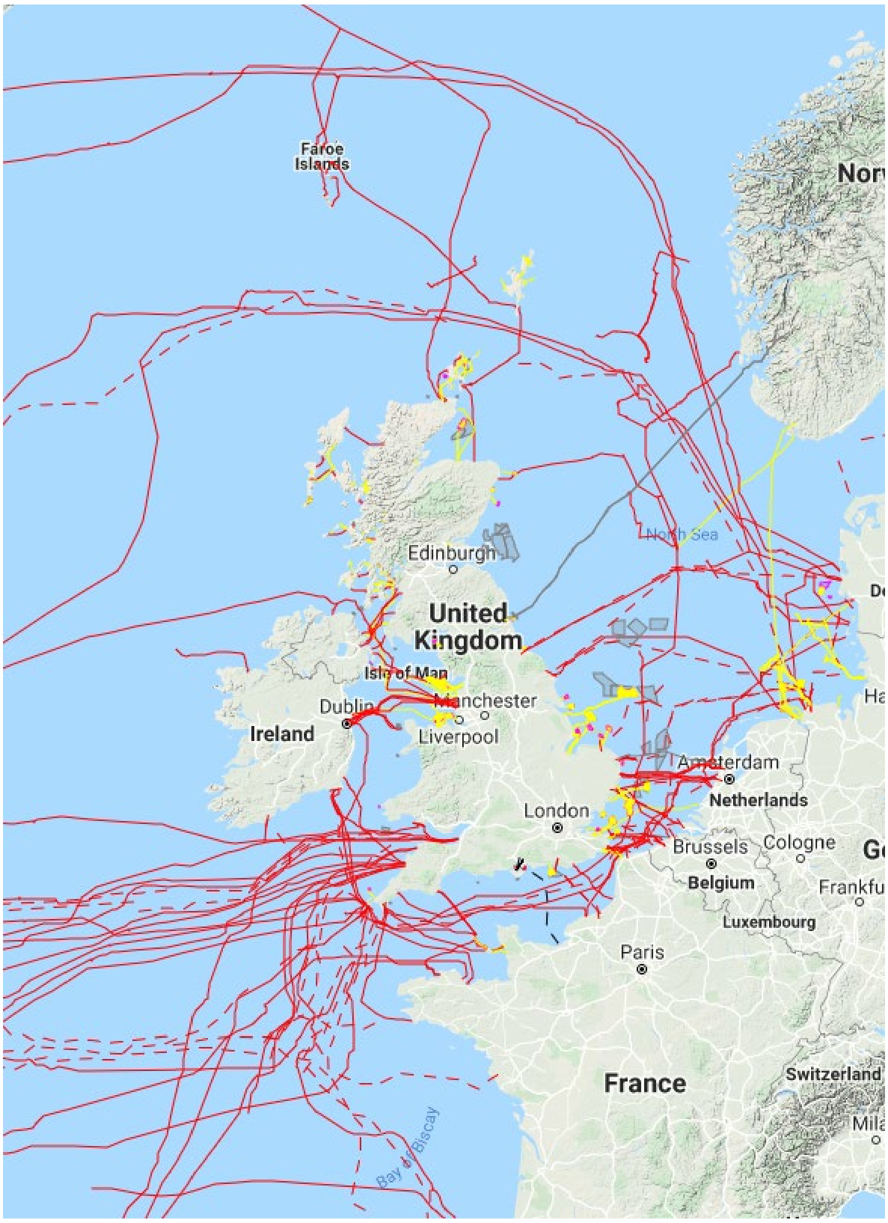

Figure 3. Subsea cables found around the United Kingdom. Red = telecommunication cables, yellow = power cables, black = proposed cables. Map produced by Kingfisher Information Service – Offshore Renewable & Cable Awareness project (*From* KIS-ORCA).

1.4. Multi-stressors

In natural systems, crustaceans will rarely be exposed to a single stressor at any point in time; therefore, it is important to consider possible effects of multiple stressors, including both natural and anthropogenic stressors [e.g. 87–90]. Due to the highly complex nature of the analysis and interpretation of multi-stressor experiments this is still a developing field.

When exposed to multiple stressors the effects of the individual stressors can interact in different ways. Certain types of interactions can be classified broadly as additive, synergistic, or antagonistic[90,91] (Figure 4). Meta-analyses and reviews highlight the variability in how multiple stressors interact and the large number of factors that may influence interactions. For more details on multi-stressor interaction types, effect models used in research, and the range of influencing factors that must be considered, see Appendix 1 – Further background material.

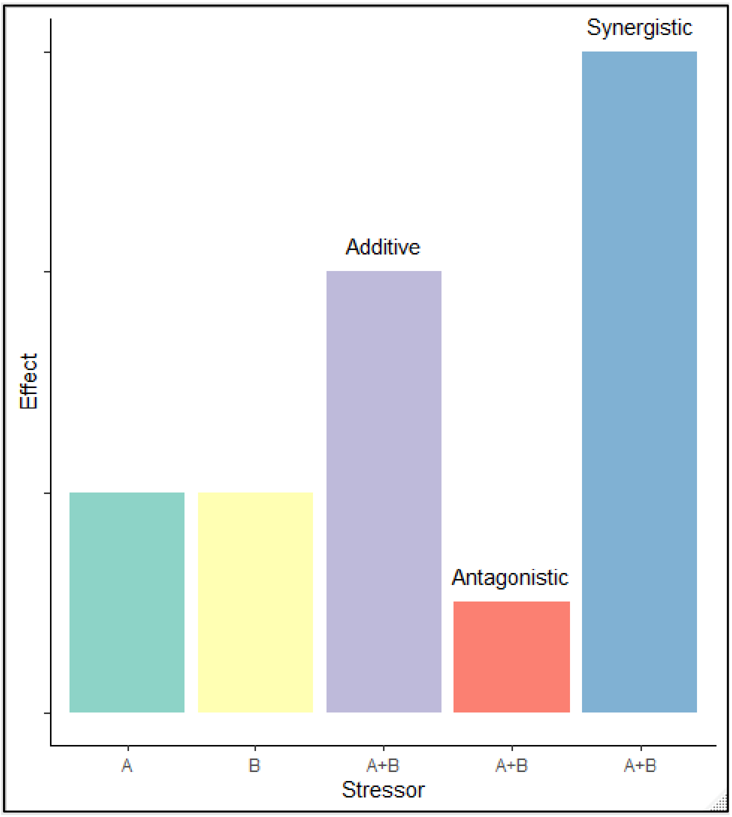

Figure 4. Conceptual diagram of multi-stressor interaction types for two stressors with the same directional effect under an additive effects model. (Adapted from Todgham and Stillman[90] and Gunderson et al.[88])

2. UK commercial crustaceans

Crustacean species in the UK that represent important commercial fisheries include:

- Brown shrimp (or North Sea prawn) (*Crangon crangon*)
- Edible crab (or brown crab) (*Cancer pagurus*)
- European lobster (*Homarus gammarus*)
- European spiny lobster (*Palinurus elephas*)
- Norway lobster (or langoustine, prawn, Dublin Bay prawn, scampi, nephrops) (*Nephrops norvegicus*)
- Velvet crab (*Necora puber*)

In 2018, crab, lobster, and Norway lobster landings from UK and foreign vessels into the UK equated to 56,800 tonnes with a value of £192.7 million[92], with Norway lobster having the highest value (£79.1 million), followed by crabs (£69.5 million) then lobsters (£44.1 million). Given their commercial importance, there has been concern about the potential impacts of MREDs on these species on an ecological and fishery scale.

2.1. Noise

Norway lobster showed reduced burrowing and movement behaviours in response to continuous and impulsive broadband noise (i.e. simulated shipping and construction noise), and increased bioirrigation in response to shipping noise only[18]. These behaviours of the Norway lobster have wider ramifications as they are important for nutrient cycling in the ecosystem[18] (an ‘ecosystem service’). There was; however, no effect on Norway lobster tissue biochemistry[18]. Additional unpublished findings have been reported in two PhD theses and associated conference presentations on Norway lobster and European lobster. It has been suggested from preliminary results, that both “busy” and “occasional” boat noise alters different parts of Norway lobster larval life cycle, and leads to a reduction in stamina to evade predators[93]. The European lobster appeared to actively avoid a noise source in a tank in both winter and summer, but to a lesser degree in winter, in which the biological drive to find shelter was thought to override disturbance to a certain extent[94].

Brown shrimp exposed to artificial white noise showed an increased feeding behaviour (likely related to a simultaneous decrease in feeding numbers of shore crabs [*Carcinus maenas*] present in the same area), but no change in feeding rate[21]. When exposed to the noises created from a working aquarium brown shrimp showed a reduction in growth and reproduction rates[23] and an increase in metabolic rates (oxygen consumption and ammonia excretion)[24].

European spiny lobster exposed to boat noise resulted in increased mobility and significant variations of haemolymphatic parameters, identified as biomarkers of stress[11,14].

For other species within the same family as UK commercially important species, seismic survey noise did not affect Dungeness crab (*Metacarcinus magister*)[4] or Southern rock lobster (*Jasus edwardsii*)[2] larvae development or mortality, or American lobster (*Homarus americanus*) mortality or mechanosensory systems[17]. Seismic survey noise did increase American lobster feeding rate and alter their biochemistry[17], and damaged Southern rock lobster statocyst, which in turn impaired their righting reflex[13]. Physiologically, seismic exposure also led to changes in the Southern rock lobster immune system, but had no effect on other haematological parameters or hepatopancreas weight[16].

Although it may follow reason that the effects of anthropogenic noise seen in other crustacean species may similarly influence commercially important UK species, conflicting findings (e.g. some species showing larval effects of noise, whilst some reporting no effects) suggest that influences may be specific to smaller groups within crustaceans[67]. There is the possibility that there may be inter- and intraspecific variability in the susceptibility to (and recovery from) anthropogenic noise and vibration, again precluding the ability to draw significant conclusions for UK species. It is therefore necessary for research specific to UK commercially important species to be conducted.

2.2. EMF

Scott et al.[38] highlighted that during exposure to a static DC EMF of the strength predicted around windfarm subsea power cables, edible crabs exhibit significant behavioural and physiological changes. A clear attraction to EMF was found to exist within this species with individuals being drawn to the emission source and significant amounts of time being spent within the EMF area. This behavioural change may come at the cost of time spent foraging for food, seeking mates, and finding shelter, potentially leading to higher predation rates, increased death due to starvation and/or decreased number of successful matings, if the behaviour persists long-term[38].

Within the same study a strong physiological change was noted during exposure to EMF, with significant changes in the haemolymph parameters ʟ-Lactate and ᴅ-Glucose. ᴅ-Glucose, the primary fuel for Adenosine Triphosphate (ATP) production in crustaceans, is crucial in maintaining metabolic processes[95]. ʟ-Lactate is an indicator of anaerobic respiration, typically due to impaired gill function or hypoxic conditions[96]. Changes in both parameters, which should cycle together in normal unstressed conditions[97], suggest that melatonin (a neuropeptide present in crustaceans) secretion has been altered. This has also been confirmed in several other species during exposure to EMF[98–102]. The potential aggregation of edible crab around benthic cables and the subsequent physiological changes in ʟ-Lactate and ᴅ-Glucose levels, brought about by EMF exposure, is a cause for concern and further research is needed to address the many knowledge gaps that still exist for this species. For closely related species, EMF exposure had no effect on rock crabs, and showed mixed responses from Dungeness crabs[43,103,104].

The only peer reviewed study to date on live European lobster, conducted by Taormina et al.[105], found that exposure to an EMF of 0.23 mT had no adverse effects on certain behaviours; although, the study was limited to juvenile lobsters. Results of European lobster behaviour during exposure to EMF in a PhD thesis was mixed[106]. Dissected giant axons from nerve bundles in European lobsters were not affected by EMFs, but it was suggested that nerve excitation by magnetic field influence may be mediated by a different mechanism[107]. In the field the closely related American lobster was not affected by exposure to EMF[108].

Short pulses of a high strength EMF have been shown to affect the internal compass of Caribbean spiny lobster, which may affect the lobsters' ability to navigate their environment[35]. The closely related European spiny lobster may exhibit similar results given similar behaviour and physiology; however, to date there have been no studies on this species with regards to EMF exposure within the UK to the authors knowledge.

Bochert & Zettler determined there were no significant differences in the survival of brown shrimp during a seven week exposure to a static EMF[109].

Even though many offshore sites introduce no-take zones around turbine arrays, with speculation that the decrease in fishing pressure, combined with the addition of artificial reefs in the form of scour protection blocks, could enhance the overall crustacean population[110] by providing refuge and breeding areas, the behavioural changes highlighted by Scott et al.[38] suggest a potential lack of spill-over effect from these areas due to a high attraction to the emitted EMF (Figure 5). This suggests that fishing zones in close proximity to subsea power cables could potentially see an overall decrease in crab numbers.

Figure 5. Image of Edible crab (*Cancer pagurus*) attraction to a simulated subsea cable.

3. Literature review

3.1. Underwater sound & vibration

Details of the potential effects of noise on several crustacean parameters (behaviour, physiology, development and early life stages, reproduction, fishery catch rates and yields and mortality) are described in the following sections. Appendix 3 – Anthropogenic noise & crustacean research, provides a summary table of these papers by species.

Table 2 summarises whether anthropogenic noise and vibration had an influence on the crustacean parameters across all of the literature found. It is worth noting that some of the studies in Table 2 investigated multiple parameters in a single study (e.g. fishery catch rates, early life stages, and physiology). In these cases, each parameter was looked at individually, meaning the same study will contribute to the tally in multiple areas.

Table 2. Summary table of the number of studies in this literature review that provide evidence of the influence of anthropogenic noise and vibration on various crustacean characteristics.

	Behaviour	**Physiology**	**Development and early life stages**	**Reproduction**	**Fishery catch rates and yields**	**Mortality**
Influence recorded	15	10	3	1	0	0
Some influence (mixed evidence)	3	2	0	0	0	0
No influence	2	2	3	1	4	4

3.1.1. Effects of noise & vibration on crustacean behaviour

Behavioural effects of noise on crustaceans has been studied most in the common European hermit crab (*Pagurus bernhardus*), with six publications, of which two focussed on vibration. These studies revealed a range of responses, including delays in reaction to predator presence[30] and reversal of grouping behaviour preference[7] when exposed to shipping and boat noise. Vibration and particle motion appear to yield alterations in behaviour, e.g. causing individuals to retreat into their shells (either partially or fully)[31], and changes in other movement behaviours known as "reception indicators"[31,34]. Two additional studies regarded the selection of an optimal shell when individuals were placed in suboptimal shells. In hermit crabs, an optimal shell is desired highly as a means of protection from various factors, such as predation and changes in salinity[8]. The potential benefit of acquiring a better shell; however, is weighed against a period of extreme vulnerability when moving from a suboptimal shell to an optimal shell, during which time individuals are exposed to predation[6]. As such, the decision of whether to move into an optimal shell can be of vital importance, and alterations in this behaviour could have ramifications on survival and reproduction[33]. It was found that shipping noise caused individuals to approach, investigate, make a decision, and enter the optimal shell more quickly[8], but fewer individuals actually chose to take the optimal shell[6,8]. When a predator presence was introduced, it was found that crabs with less optimal shells took longer to decide whether to switch to the optimal shell, but this was not seen when shipping noise was applied, implying a negation to the usual predator response[6]. These findings are mirrored in the Acadian hermit crab (*Pagurus acadianus*), in which fewer individuals moved towards a newly available optimal shell when exposed to vibrations caused by simulated pile driving[33].

Other species have been reported to have important aspects of life history disrupted by anthropogenic noise sources, such as movement and anti-predation behaviour. Increased movement has been seen in a semi-terrestrial burrowing crab (*Neohelice granulata*)[9], the mud crab (*Scylla paramamosain*)[20], European spiny lobsters (*Palinurus elephas*)[14], and Pacific white shrimp (*Litopenaeus vannamei*)[19] exposed to simulated general anthropogenic noise, simulated offshore activities, shipping noise, and simulated pile driving, respectively. The opposite was seen with an increase in resting time (plus additional time spent outside a shelter) in the common prawn (*Palaemon serratus*)[15]. Norway lobster behaviour saw a reduction in movement and burrowing behaviours in response to simulated shipping and construction noise, and an increase in bioirrigation in response to simulated shipping noise[18]. Brierley et al.[32] noted that the Antarctic krill species *Euphasia superba* did not show avoidance behaviour to a research vessel compared to a much quieter Autonomous Underwater Vehicle (AUV). The vessel noise was therefore unlikely to have an effect on krill distribution, and results of distribution surveys carried out by the research vessel in question would not be skewed by avoidance behaviour[32].

The righting reflex of a crustacean is a measure of how long it takes an upturned individual to turn over (i.e. to correct or "right" their position in the water). It is an important measure of anti-predation, as the animals are moving from a vulnerable position (with the weaker underside exposed) to a position allowing for anti-predator behaviours to take place [13,22]. It is also indicative of whether the sensory systems involved in this reflex are damaged[17]. The righting reflexes of shore crabs (*Carcinus maenas*) and Southern rock lobsters (*Jasus edwardsii*) were studied with regards to shipping noise and seismic surveys (respectively) and were found to have opposing responses. A faster righting reflex was seen in shore crabs[22], whilst an slower righting time was seen in the Southern rock lobster[13]. In contrast, this reflex was unaffected in American lobsters (*Homarus americanus*) in response to active seismic surveys[17]. In addition, reduced predator risk assessment (i.e. allowing the predator to get closer before reacting) has been noted in Caribbean hermit crabs (*Coenobita clypeatus*) exposed to boat motor playback[29].

Several other studies have reported influences of sound on feeding behaviours of crustaceans. Simulated shipping noise has been demonstrated to cause some individuals of common shore crab to cease their feeding[22], whilst an increase in feeding rate was reported in American lobsters exposed to seismic airgun noise[17]. Conversely, snow crabs (*Chionoecetes opilio*) collected after an operational seismic survey were not reported to show any differences in feeding behaviours[3]. It has also been suggested that noise may shift competitive feeding balances. Broadband artificial white noise caused a decrease in common shore crab feeding aggregations, which was suggested to enable the incidental observed increase in feeding numbers of common/brown shrimp (*Crangon crangon*); however, no difference in feeding rates of individuals present around a food source was noted for either species[21].

Alterations to acoustic behaviours have also been attributed to anthropogenic noise. Changes in snapping shrimp choruses in response to simulated pile driving have been reported[10]. Three species of snapping shrimp (*Alpheus glaber, Alpheus macrocheles*, and *Athanas nitescens*) were exposed to three SPLs of simulated pile driving, and it was found that the number and amplitude of snaps increased in response to the noise. Similarly, general "human" noise generated in the lab was found to increase the number of acoustic signals emitted by *N. granulata* crab[9].

Potential distraction caused by noise is a proposed mechanism for these behavioural changes. It is hypothesised that crustaceans have a limited amount of attention to dedicate to their tasks at any given time, and the introduction of anthropogenic noise may cause distraction by requiring a portion of their attention to be turned towards unfamiliar noise[22,29]. This could elicit unusual behaviours or disproportional reactions to a threat, both of which can have further ramifications, such as increased risk of predation or loss of valuable resources[6,7,22,29].

Several studies demonstrated the potential of noise to influence behaviours not actually attributed to noise itself, suggesting "cross-modal" influences of anthropogenic sound (i.e. sound eliciting changes in behaviours facilitated by other senses)[33]. For example, shell selection in European hermit crab[8] and Acadian hermit crab[33] represent possible cross-modal influences, as the selection process of this vital resource utilises a combination of chemical, visual, and tactile cues. This is potentially important as it could imply indirect influences of sound on behaviours mediated by other sensory channels, possibly meaning that sound may have more complex and far-reaching influences than currently thought[8,33].

Overall, the reported behavioural changes could be detrimental to crustaceans if, for example:

- Increased movement or other energetic activities could cause energy reserves to be used more quickly than normal, leaving less energy available for important functions such as growth, reproductive success, and escaping from predators[10,20,25].
- Stressful stimuli reduce appetite and foraging behaviours[22] which may decrease the likelihood of animals gaining enough nutrition. This could be particularly important for the highly competitive decapod crustaceans who are likely to lose their food source if they move away from it when disturbed[22]. These changes to nutrition could influence important life factors in a similar way to the reduction in energetic stores.
- Changes in feeding behaviour alter the natural balance of feeding competition in the wild[21].
- The different distribution of individuals in the short-term lead to higher level impacts[14].
- There is an increased risk of predation through disruption of anti-predator behaviours or by drawing attention with noise[10,13,17,22,29].Changes to noises emissions could have ramifications for communication abilities, which may influence behaviours relating to reproduction or warning others of predator presence[9].

It is important to note; however, that on the basis of available evidence it is currently unknown whether the behavioural changes noted could be significant enough to lead to such eventualities.

3.1.2. Effects of noise on crustacean physiology

One measure of physiology is metabolism, which includes oxygen consumption. A size-dependent increase in oxygen consumption (i.e. larger responses seen in heavier individuals) has been reported in common shore crab exposed to single ship playback (although this was not seen in repeated ship playback)[25]. This suggests that larger individuals are more susceptible to deleterious influences of acute sound. The constant "high" noise levels associated with a working aquarium have been shown to increase the oxygen consumption and ammonia excretion rates of brown shrimp[24]. Unless an increased metabolism is accompanied by increased feeding, energetic imbalances could cause negative influences on important life factors including growth and reproduction[25]. A reduction in brown shrimp growth rate due to metabolic changes and reduction of food intake has been postulated, although not investigated specifically[23].

Abnormal levels of some substances in the haemolymph (crustacean "blood"), tissues, or expression of particular genes can also indicate whether an animal perceives a certain stimulus as stressful or threatening. Organ "stress" can be measured by looking at physical changes to organs (such as the hepatopancreas), or by looking at the levels of some enzymes in the blood, which become higher if the associated organs are damaged[17]. Additional measurements of the levels of certain cells or various substances in the haemolymph can suggest that normal processes are going wrong or can be reflective of the organism's body trying to adjust to their environment and cope with stress[16]. Some of these parameters have also been suggested to be indicative of immune alterations, which may increase chances of infections[11,14,16].

Significant changes in the levels of some factors in the haemolymph have been reported in American lobster[17] and Southern rock lobster[16] in response to seismic air gun noise, and in common prawn[15] and European spiny lobster[11,14] in response to boat and shipping noise. *N. granulata*[9] has also shown changes to such factors in response to laboratory generated noise mimicking general anthropogenic noise. In response to airgun noise, American lobsters also exhibited changes to the hepatopancreas (an organ in crustaceans which is similar to a combination of a pancreas and liver) four months after exposure[17]. At a genetic level, increases in the expression of a certain group of proteins (called Heat Shock Proteins [HSPs]) indicative of stress were noted in European spiny lobster[11,14], mud crab[20], and the common prawn[15].

In contrast, some studies have shown a lack of changes to these parameters following exposure to anthropogenic sound. For example, noise mimicking offshore shipping sound (continuous and impulsive) was found to have no effect on the concentration of various substances in the tissues of Norway lobster[18], and active seismic surveys were not linked with any alterations to a range of substances measured in haemolymph and tissues, or physical changes to body structures or tissue of organs (hepatopancreas or heart) in snow crab[3,12]. The previous study by Fitzgibbon et al.[16] which showed changes in some parameters of the haemolymph of Southern rock lobster also showed a lack of effect on other factors measured in the haemolymph, and no change in the hepatopancreas index (which is a relative measure of the size of the body versus the hepatopancreas, and can indicate the nutritional condition of an animal).

Day et al.[13] observed damage to tiny hairs on the statocysts of Southern rock lobster after exposure to seismic air guns signals. In addition, they reported that this damage did not improve even after the animals had moulted, or until the end of observation period (up to one year), suggesting that there could be longer term detrimental impacts associated with seismic air guns[13].

3.1.3. Effects of noise & vibration on crustacean mortality, reproduction & early life stages

Reproductive abilities, egg development, and larval health are vital for populations of animals. If an imbalance is caused through an increased death rate, reduced reproductive rates, or lowered larval survival, population levels will begin to fall. Whilst no studies have indicated a direct effect of anthropogenic noise on mortality (immediate or delayed)[3,12,17,27], influences have been noted on early life stages and reproduction.

Varying results have been reported on the influence of artificial marine noise on crustacean development and larval fitness. Delayed metamorphosis has been reported in two estuarine species, the tunnelling mud crab (*Austrohelice crassa*) and hairy-handed crab (*Hemigrapsus crenulatus*), in response to sound emitted from tidal and wind turbines[5]. Acorn barnacles (*Balanus amphitrite*) were similarly found to show delayed metamorphosis in response to a ship anti-fouling device (the Hydro-Sonic Hull tender) which emits noise[1]. The Hydro-Sonic Hull Tender also reduced the attachment abilities of acorn barnacles (an important part of the life cycle of a barnacle, when the last larval stage finds somewhere suitable to permanently attach and become a sessile adult)[1].

Figure 5. Image of a European lobster (*Homarus gammarus*) larvae.

Seismic air gun noise is postulated to be of particular concern regarding egg and larval development, as crustacean larvae (Figure 6) are released into the upper portion of the water column, potentially into close range of seismic surveys[4]. Air gun noise has been suggested to stunt the development of snow crab eggs[12]. However, a lack of influence has also been noted on the development of snow crab larvae, or their ability to move after hatching, following a seismic survey[3]. These results have been mirrored in the Dungeness crab[4] and southern rock lobster[2], who also did not show changes to larval development or health (including survival) following seismic air gun exposure. Fewer studies have looked specifically at the effects of noise on the reproductive capabilities of female crustacea. Lagardère[23] indicated that aquarium noise caused the time to first spawning for brown shrimp to be delayed whilst reducing the ability of individual females to spawn multiple times during the period of the study (April – June of the same year). In addition, a longer time for egg development was seen, suggesting an overall decrease in reproduction rates. It was hypothesised that these may have been indirect effects, with noise-induced stress affecting the feeding and metabolism of the females and therefore influencing reproduction, but this hypothesis was not tested. Changes to reproductive capabilities did not occur for Southern rock lobster, which did not appear to show any differences in fecundity after exposure to seismic air gun noise, as evidenced by a lack of egg bundle loss and similar average numbers of hatched larvae[2].

3.1.4. Effects of noise on fishery catch rates and yields

To date, no studies have indicated any effects of anthropogenic noise on UK commercial crustacean fishery catch rates or yields. However, the only source of noise studied has been seismic surveys. Four studies have evaluated the potential influences of this on several species.

Two of these studies investigated the influences of seismic surveys with regards to catch rates of snow crabs in Canada[12,27]. The first looked at the catchability of crabs exposed to an airgun array of 3.28 l air volume, consisting of 7 airguns (2 x 0.16 l, 1 x 0.33 l, and 4 x 0.65 l). Crabs were exposed to 200-1,000 shots, and the time after exposure was 2-292 hours. Controlled fishing was conducted close to the sound source both before and after the seismic survey using fleets of 40 traps baited with squid. It was found that the catch after the seismic exposure was actually higher than before, but this was attributed to other factors unrelated to the seismic source. It is also noteworthy that “considerable variability” was noted for a number of factors (e.g. soak times for traps used and likely received level of sound by individual crabs)[12].

The second study on snow crabs was conducted around seismic surveys during two consecutive years (2015 and 2016). In both years, the airgun array was 80 l and shots were conducted at intervals of 10 seconds at a depth of 9 m. In 2015, industrial exploration took place over five days, whereas in 2016, the survey was conducted in two hours on a single day. Industrial harvesters were used to conduct catch surveys using standard fishing practices (10 baited traps per string, placed 46 m apart) at the seismic site and a control site. Catch surveys were conducted in three trips during each year, each trip ranging between three to eight days in duration. In 2015, two of the trips took place before the survey and the third afterwards. In 2016, the seismic survey took place during one of the days on the second harvesting trip. Whilst the catch rates varied at each site and in each year, it was determined that these were likely due to other factors, or that any potential influences of seismic surveys were likely of less influence than these other factors. As such, the conclusion was that seismic surveys did not negatively affect the short- or long-term catch rates (i.e. over days or weeks) of snow crabs[12,27].

The bottom trawl yields of three shrimp fisheries (*Litopenaeus schmitti, Farfantepenaeus subtilis*, or *Xyphopenaeus kroyeri)* were investigated with regards to seismic surveys in Brazil. Seismic surveys were conducted in a period of a little under one month (15 March–02 April 2002) using 10.4 l arrays of four airguns, shooting at intervals of 12 seconds. The study site was split into eight sectors, and the shrimp catch rates (weight per hour and number of each species per hour) were ascertained in each sector via trawls both before and after exposure. A total of 46 trawls were conducted before seismic exposure, and 46 afterwards. Whilst the initial protocol defined that post-exposure trawls would be conducted the day after seismic exposure, sea conditions prevented this from always being the case. The maximum duration of time between seismic survey and the post-exposure trawl was three days. The final conclusion of the study was that, whilst other factors must be taken into consideration (such as the chance for shrimp from neighbouring sites to enter the study area), no significant damaging effect of seismic surveys was seen on the catch rates of these three species[26].

The final study analysed historic records of seismic surveys and rock lobster catch rates in western Victoria, Australia, over a period of 26 years (1978-2004)[28]. Data were analysed by a number of site and array characteristics (number of airguns, volume, pressure, depth, number of arrays, and number of airgun shots), and an estimation of relative intensity of surveys on the seabed were ascertained. The Catch Per Unit Effort (CPUE) during the entire fishing season before and after said surveys were analysed and found them to be unaffected after seismic discharges. It was pointed out that this finding was consistent with the "limited information" regarding the influences of seismic surveys on invertebrate physiology at the time (2006). It has since been demonstrated that there may be physiological effects of "unnatural" noise on crustacean species. Furthermore, it was noted that most of the seismic surveys investigated occurred in deeper waters where effects would be "expected to be minimal", and those which were conducted in shallower areas had lower levels of rock lobsters[28].

3.1.5. Summary of existing knowledge in underwater noise and vibration

A range of influences (or lack of influences) on behaviour, physiology, early life stages, and reproduction have been noted on a variety of crustaceans; however, the extent to which these changes could impact species at a population level remains unknown. To date, no effect or influence of noise or vibrations has been reported on mortality rates or fishery catch rates or yields. The lack of effects seen in such studies could be due to a number of factors, including the sound and/or vibration levels of some anthropogenic activities not being high enough to cause detrimental effects, some species being more resilient to noise and vibration than others, and study design or lack of repeated studies negating the possibility of conclusive answers. Appendix 3 – Anthropogenic noise & crustacean research, provides an overview of the noise and vibration studies performed.

Overall, this area is still relatively poorly understood, and further studies (with a focus on experimental design, ability to replicate and compare, and draw overall conclusions) are required for definitive answers to be given.

3.2. Electromagnetic fields

The range of EMF strengths that crustaceans may be able to detect is unknown. The Earth's natural geomagnetic field varies from 30 to 70 µT[16], which suggests that crustaceans are reliably able to detect EMF strengths within this range, and presumably with an acute sensitivity, particularly in those crustaceans known to undertake large scale migrations. Although, given the lack of studies investigating the detectability and sensitivity of EMF within crustaceans, the use of responses elicited throughout previous experiments provides the only insight. The lowest recorded DC field strength that elicited a response by a crustacean found within the literature was 0.1 mT by spinycheek crayfish (*Orconectes limosus*)[39] and the highest confirmed strength of 85 mT by Caribbean spiny lobster[35] (Figure 7). With an AC EMF the lowest recorded strength to elicit a response was 1 µT by the Danube crayfish (*Astacus leptodactylus*), with the highest field strength shown to cause a response of 400 µT from the same study[48]. A summary of all EMF studies to-date is found in Appendix 4 – EMF & crustacean research.

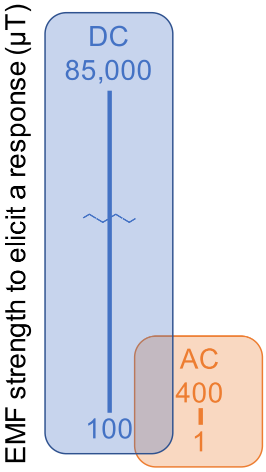

Figure 6. Highest and lowest Direct Current (DC) and Alternating Current (AC) strengths to elicit responses in crustaceans to-date.

3.2.1. Effects of EMF on crustacean behaviour

Most of the literature to date on the effects of EMF on crustaceans has focused on behavioural changes. Studies on the Caribbean spiny lobster have confirmed utilisation of the Earth's geomagnetic field during the extensive annual migrations undertaken by this species[36]. Ernst and Lohmann[35] determined that short pulses of a high strength EMF can affect the internal compass of Caribbean spiny lobster, which may affect the lobsters' ability to navigate their environment. Given the prevailing thought that crustaceans sense EMF through magnetite crystals within tissue cells, this suggests that most crustaceans are likely to be sensitive to changes within magnetic fields. Several studies conducted on the Isopod, *Idotea baltica basteri,* and Amphipod, *Talorchestia martensii*[40–42], confirmed that behavioural changes occurred when the Earth's natural geomagnetic field was removed (i.e. creating an 'Earth zeroed field'). The organisms had difficulty identifying the ecologically efficient orientation direction (land-sea axis) resulting in more time spent exhibiting body scanning behaviour which was found to be used by Isopods and Amphipods in the detection of the magnetic symmetry plane.

Studies conducted on the Dungeness crab and edible crab have also confirmed behavioural changes during exposure to increased EMF. Both species showed increased activity when compared to non-exposed crabs, suggesting a form of restlessness, when exposed to EMF of 1 mT (Dungeness crab) and 2.8 mT (edible crab)[38,43]. The study on Dungeness crab also found that the crabs spent less time buried in the sand, a natural behaviour involved in predator avoidance, when exposed to EMF. The study on edible crab saw an attraction to the source of the EMF, which may come at the expense of natural exploratory behaviour. Rosaria & Martin[37] highlighted that freshwater crab (*Barytelphusa cunicularis*) showed increased aggression and were attracted to the emission source when exposed to a low frequency EMF[24].

Research on the impacts of EMF exposure on European lobster behaviour is currently limited. A study by Taormina et al.[105] conducted on juveniles during exposure to a 200 µT EMF, found no changes in behaviour, specifically shelter-seeking behaviour. The same study acknowledges that further research is required, as different life stages may react differently to EMF exposure. An early study showed that adult lobsters were attracted to the source of an EMF (2.8 mT) and spent a higher percentage of time within the shelter exposed to EMF[106]. The discrepancies between these two studies including different EMF strengths utilised, different life stages, and different experimental methodologies highlight the problematic nature of assessing behavioural changes based solely on current literature.

Exposure to static DC fields on the red swamp crayfish/Louisiana crawfish (*Procamburus clarkii*) has been shown to affect the efficacy of neurotransmission in the network which mediates escape behaviour[45]. This may result in EMF exposure making the internal 'escape circuit' more sensitive to external stimuli for tail-flip escape behaviour.

3.2.2. Effects of EMF on crustacean physiology

Exposure to EMF has been shown to affect a variety of physiological processes within crustaceans. Lee & Weiss[46] demonstrated that EMF exposure affected moulting in fiddler crabs (*Uca pugilator* and *Uca pugnax*). Whilst the exact processes involved in this response were unclear it was postulated that the effects of EMF on enzymatic reactions and ionic flux, in addition to electric currents present within the autotomised limb stumps, led to a delayed response in those in close proximity to the north pole EMF. Studies on the effects of EMF exposure on neurons in Danube crayfish[48], and on neurotransmission within Louisiana crawfish[45], both highlight potential changes in internal cellular state including membrane processes, mitochondrial function, glycolysis, and protein synthesis.

A link between serotonin levels and both increased aggressiveness and feeding behaviour of crustaceans has been confirmed[37,111]. Several studies indicate that EMF effects serotonin regulation[112,113], suggesting EMF exposure affects the internal physiology of crustaceans which results in subsequent behavioural changes.

Melatonin has also been shown to be affected by EMF exposure in several species[98–102] and is thought to be the primary factor responsible for the haemolymph parameter disruption found to occur in edible crab during EMF exposure.

A presumed change in melatonin levels brought about by exposure to a 2.8 mT EMF resulted in significant changes to ʟ-Lactate and ᴅ-Glucose circadian rhythms in European lobsters[106]. During exposure haemolymph ᴅ-Glucose concentrations were significantly elevated throughout the 24-hour experiment whilst ʟ-Lactate concentrations were significantly elevated after a period of 12 hours. These physiological changes suggest increased anaerobic respiration and the possible onset of mild hyperglycaemia. In the same study it was determined that an immune response was being elicited during exposure to EMF with an initial significant decrease in haemocytes and subsequent increase after 24 hours of exposure compared to control lobsters. More standardised studies are required to determine the effects of chronic EMF exposure on crustacean physiology.

3.2.3. Effects of EMF on crustacean life history and development

Studies on the effects of EMF exposure on the early life history and development in crustaceans are currently lacking.

EMF exposure (2.8 mT) resulted in varying egg volumes for edible crabs compared to control crabs (i.e. unexposed) and exposed larvae were significantly smaller, but there were no statistically significant differences in hatched larval numbers, deformities, mortalities, or fitness[106]. European lobsters exposed to EMF were found to have a significant decrease in egg volume at later stages of egg development, more larval deformities, lower larval fitness, and smaller total larval length, carapace height, and eye diameter[106].

Shckorbatov et al.[47] reported that exposure to EMF resulted in a higher hatching percentage from exposed brine shrimp (*Artemia* sp.) cysts. It was hypothesised that EMF exposure, acting as a stressor, promoted the activation of the dormant blastula cysts.

Given the life history of many crustacean species and the high probability of coming into contact with subsea power cables and the resultant EMF, further research needs to include early life history and development.

3.3. Multi-stressors

Various temporal and spatial regimes of noise and EMF exposure will occur during all phases of MRED survey, construction, operation, and decommissioning, with varying degrees of intensity. A review of the different noises created during an offshore wind farm's life cycle is provided by Nedwell and Howell[114]. Other reviews summarise the multiple stressors and changes that may occur from MREDs[51,115,116]; but, to-date, there is no published literature on the combined effects of noise and EMF exposure on crustaceans. Due to the high variance in multi-stressor interaction types and the strong effect all factors have on the interaction type, it is difficult to say for certain how crustaceans may respond to combined noise and EMF stressors[87].

3.3.1. Noise & other stressors

The co-occurrence of pile-driving noise and toxic trace metal cadmium increased the adverse effects on various metabolic processes in the blood clam (*Tegillarca granosa*), but as this study did not have a treatment group which was exposed to noise only, conclusions cannot be drawn regarding the difference between individual stressors or possible interactions of multiple stressors[117]. A similar study looked at cargo-ship noise and cadmium in Pacific oysters (*Magallana gigas*), and found that while ship noise decreased the bioaccumulation of cadmium this was likely due to oysters spending more time closed, and thereby a decrease in feeding, which also meant there was a reduction in growth rate[118].

Dolédec and Statzner[119] detected changes in a variety of general biological invertebrate traits in large European river reaches exposed to heavy metal pollution and cargo-ship traffic, with cargo-ship traffic dominating the changes. The authors suggest that cargo-ship traffic effects may dominate because pollutant levels may not have been high enough to be detected, or the wrong trait categories may have been used[119].

Further research addressing the potential multi-stressor effects of anthropogenic noise and chemical pollutants on multiple levels of biological organisation within selected model species, including crustaceans, is currently ongoing[120].

There was no interaction effect of short-term elevated CO_2 in combination with boat noise on predator (dottyback, *Pseudochromis fuscus*) prey interactions (juvenile damselfish, *Pomacentrus wardi*)[121] or with pile driving noise on European sea bass (*Dicentrarchus labrax*) ventilation rate or startle response[122]. This may be due to the stressors working through two different mechanisms[121], or a maximum stress level being reached from one stressor[122]. To an extent (also due to a possible stress threshold), two coral reef fish (*Chromis viridis* and *Acanthrochromis polyacanthus*) have shown some increased stress to boat noise after being subject to suboptimal dietary conditions[123].

3.3.2. Survey

Prior to constructing MREDs various surveys of the seabed are undertaken. During this time animals may be exposed to short-term exposure of low-level noise from survey vessel(s) and equipment (e.g. multi-beam echo sounder, side scan sonar, sub-bottom profiler). Studies that look at the effects of noise on crustaceans have focused on oil and gas related seismic survey noise, which in many cases will have a higher SPL than the survey equipment used for MREDs (Table 4 in Appendix 1).

The small number of studies in this field have shown that there is no evidence of an effect of seismic surveys on the catch rates of various crustacean species[12,26–28]. Results from other response variables have been mixed. Studies have shown no effect on adult mortality or haematological and histopathological indices[12,16,17], fecundity or embryonic development[2,124], and larval development or mortality[4]. Whereas the same studies have shown stunted development of eggs[12], increased adult feeding rate and changes in serum biochemistry[17], damage to mechanosensory organs and impairment of righting reflex[13], and changes in the immune system[16].

Studies investigating ship or boat noise in isolation, have focused mainly on behavioural responses, and have seen a variety of changes, for example:

- Disrupted feeding behaviour, slower anti-predator response, and faster righting time[22]
- Reduced predator risk assessment[29]
- Reduced vigilance[30]
- Changes in shell choice[6,8]
- Changes in grouping behaviour[7]
- Increased time resting and time outside of shelter[15]
- Increased movement[14]

Physiological[25] and biochemical changes[11,14,15] were also seen in some species of crustaceans. Shipping and boat noise has also been shown to not affect avoidance behaviour in krill (*E. superba*)[32], or predator response and emergence time in the European common hermit crab[30].

Many of the seismic studies were conducted in the field either during industrial seismic surveys[26–28,124] or at least with seismic survey vessels[2,13,16]; therefore, animals would have been exposed to seismic pulses and vessel noise simultaneously, giving a final multi-stressor response.

3.3.3. Construction

During construction, crustaceans may be exposed to noise from explosive detonation, pile driving, and construction vessels and other activities. This is likely to be the noisiest phase of an MRED project[125].

The different phases of survey and construction both have the potential to effect crustacean behaviour and/or biochemistry. If the time between stressors is less than the amount of time required for recovery temporal accumulation may occur[126], and the effect(s) of the stressors may interact. Exactly how the varying stressors might interact or whether the same individuals would be exposed to all stages of survey and construction are too difficult to say without further investigation.

Playback and mechanically simulated (drubbing of bamboo pole) pile driving noise exposure affected the acoustic behaviour of snapping shrimp species[10] and significantly increased the motility of whiteleg shrimp[19]. Some studies have used lab generated noise to simulate construction or pile driving noise, and have also found increased locomotion[9,20] and changes in acoustic behaviour[9]; in addition to changes in gene expression[20], biochemical alterations in some cases[9] but not others[18], and a case with Norway lobster when there was a reduction in movement and burrowing[18].

Studies on the effects of substrate borne vibration on crustacean behaviour have found changes in chemically-guided search behaviour[33], movement of the second antenna, and onset or cessation of locomotion[34].

Additional stressors that crustaceans may be exposed to during construction, which may affect how they respond to noise stressors, include, but are not limited to:

- Explosions[127,128] from the detonation of Unexploded Ordnance (UXO)
- Sediment suspension[129]
- Release of heavy metals and other contaminants[130,131]
- Dredging[132]
- Cable laying and burying[133,134]

3.3.4. Operation

Noise exposure during operation (running MRED and service vessels) will occur continuously for the long-term and at lower intensity than during construction, and EMF from seabed cables will be introduced, leading to the potential for simultaneous noise and EMF exposure (Figure 8). The locations for which this has the possibility of occurring will depend on the size of the EMF field around the cables and their interaction, and the distance the noise of the MRED and service vessels propagates.

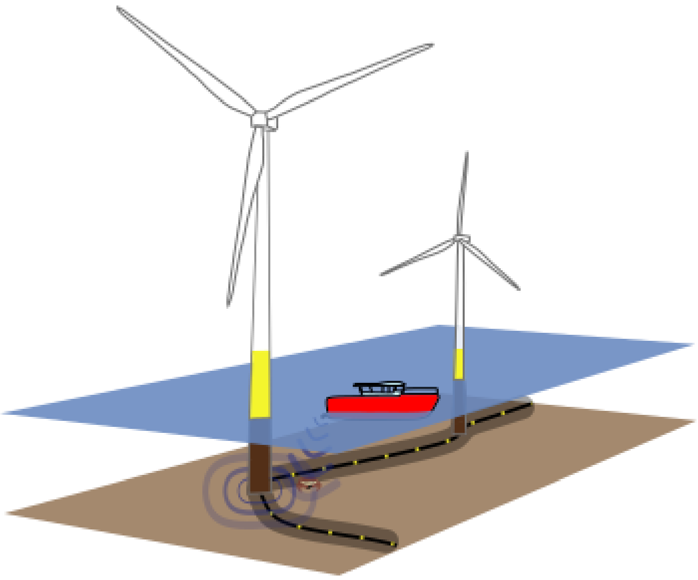

Figure 7. An edible crab (*Cancer pagurus*) exposed simultaneously to an Electromagnetic Field (EMF) from subsea power cables and noise from a vessel and operational wind turbine.

The continuous nature of MRED operation means there will be little reprieve for animals exposed simultaneously to potential noise and EMF stressors, which may lead to a synergistic interaction[88]. Being mobile species crustaceans are capable of moving away from potential stressors, but if changes in orientation[35,36,41,42] and movement[43,108] behaviour due to altered EMFs (including attraction to EMF[38]) are stronger than the desire to move away from noise, there is the potential these stressors may interact. The noise generated from vessels servicing MREDs also has the potential to affect crustacean behaviour[6–8,15,22,29,30]. However, there are also examples of shipping and boat noise and EMF having no effect on crustacean behaviour[30,32,104], survival[109], and fisheries[12,26–28,103].

Pine et al.[5] found turbine noise delayed the median Time To Metamorphosis (TTM) by at least 18 h in estuarine crabs (*A. crassa* and *H. crenulatus*), and EMF has been shown to effect brine shrimp hatching and larvae[47]. Taormina et al.[105] found juvenile European lobsters did not exhibit any change of behaviour when submitted to an artificial magnetic field gradient.

Hubert et al.[21] found white noise reduced the cumulative counts of the common shore crab that aggregated at a food item, and Wale et al.[22] saw a disruption in shore crab feeding behaviour when exposed to shipping noise, whilst Rosaria and Martin[37] found low frequency EMF induced freshwater crabs to increase their feeding rate.

Physiological[25,38] and biochemical[11,14,15] changes were also seen in some species of crustaceans during exposure to noise and EMF separately; therefore, there is the possibility that these responses may interact.

Possible additional stressors during MRED operation that may also interact with the potential effects of noise and EMF include:

- Leaching of anti-fouling paint
- Possible leaks and spills (i.e. hydraulic fluid)
- Temperature increase around cables
- Changes in sediment transport and deposition[116]

Additional changes to the surrounding habitat will also occur from the physical presence of the MRED structures in the sea and fishing restrictions within and around the MREDs[110,116,135]. Scour protection around the base of MREDs to reduce erosion acts as artificial reefs and subsequently creates up to 2.5 times more habitat than that lost by array installation, albeit it may be of a different character[136]. MREDs may; therefore, increase biodiversity through new habitat creation[135,137,138]. Various crustaceans and life stages have been found on the hard substrate of monopiles[139–142]. Langhamer and Wilhelmsson[110] showed that a significantly higher abundance of fish and crabs were present on the turbine foundations compared to the surrounding soft bottoms. A five-fold increase was seen in the number of edible crabs present when holes were drilled into the scour zones. Krone et al.[143,144] showed that edible crab numbers doubled on turbines with scour protection zones. Horns Rev offshore windfarm in Denmark saw an increase in edible crab total biomass during the first few years of operation[140].

In the short-term, Offshore Wind Farm Egmond aan Zee in the Netherlands had no statistically significant differences in benthic communities inside the finished windfarm compared to reference areas outside the windfarm[145], but later on they saw a considerable increase in small crustacean species (order Amphipoda) on the hard substrate of the monopiles and scour protection layer[138].

This increased capacity for benthic and pelagic organisms, combined with the no-take fishery zones (typically 50 m from turbines, and often surrounding the entire array of turbines) commonly implemented around offshore windfarms may cause a spill-over effect, with nearby fished areas possibly seeing an increase in catch[146–149]. However, further research is needed to determine what impact the deployments and subsequent increased noise, vibration, and EMF will have on crustaceans.

3.3.5. Decommissioning

Effects during decommissioning will likely be similar to those during construction, with relatively short-term noise stressors from increased vessel activity. Some sites may also consider refurbishments or repowering (i.e. replacing existing turbines with more powerful ones), which may involve additional pile driving noise.

During all stages, crustaceans may also be exposed to other anthropogenic stressors (i.e. global climate change) at the same time as noise and EMF exposure, which could lead to a more intense negative effect[87,150].

4. Knowledge gaps & future research

4.1. Limitations & knowledge gaps

There are significant gaps in knowledge surrounding the use and detection of sound and vibration in crustaceans and the potential influence of anthropogenic activities, despite their commercial importance and the fact that influences in the lower trophic levels could have knock on effects for animals further up food webs[72].

The background research into the sensitivity of crustaceans to noise and vibration highlights our limited understanding of how these creatures detect and utilise noise. The studies tended to focus on observing behavioural indices in a narrow range of frequency, as opposed to exposing individuals to a wide range of noise and determining full detection ranges.

Another factor preventing the ability to draw conclusions from existing research is a lack of consistency across studies. There is considerable variation in experimental design, sound parameters measured, and units used for reported parameters, which cannot be compared directly. In addition, some papers lack robust reporting of methodologies and measured parameters[151], an issue in both noise and EMF research. Such issues preclude the ability to repeat studies, or derive direct comparisons between studies or any overall conclusions[67,74,152].

The inconsistency of measured sound parameters calls into question the value of previous research, as it has been argued that the selection of parameters has been largely inappropriate to study crustaceans[72,73]. Vibration and particle motion, the aspects of sound important to crustaceans[67,74], have been particularly understudied[73], showing a lack of defined measures or techniques[16]. SPL, which is relevant for marine mammals and finfish, and often used in licencing stipulations, has been the most widely measured parameter of anthropogenic noise in crustacean research, even though it has been suggested that the pressure components of sound may not be as influential to crustaceans and other invertebrates owing to the lack of gas-filled organs or cavities[34,72,74].

Despite likely being of large influence on crustaceans due to significant increases to vibration and particle motion, pile driving noise has only been considered in a few papers. In addition, only one paper specifically observed effects of the running noise of tidal and wind turbines, despite the increasing rate of wind turbine development.

There are also clear gaps in the literature of the effects of EMF on crustaceans worldwide. The few studies available on UK species were conducted using different types and strength of EMF, experimental methodology, and assessed different experimental parameters, making comparisons difficult. The differences in results obtained between species that occupy similar biological niches such as edible crabs and European lobsters highlights the importance of species-specific studies as opposed to biological categorisation currently utilised within Environmental Impact Assessments (EIAs). More importantly however, is the need for standardised methodology and EMF strengths to allow for easier comparisons and ultimately more informed management. There is a lack of in situ EMF measurements around subsea power cables and MRED deployments, which most likely accounts for the large variety in experimental values used in research. To date most values have been derived from computer models designed to predict EMF discharge and subsequent field strengths based on cable type, length, current, and capacity.

Another necessary area explored by relatively few papers is the combined and long-term cumulative effects of noise[153] and EMF. Practically nothing is known about the cumulative impacts of the anthropogenic soundscape on crustaceans[154] or how organisms may recover from sound[18], including whether chronic exposure to anthropogenic noise allows for habituation or behavioural changes to accommodate the increased noise[70], or whether it prevents recovery. The interplay of multiple sources of anthropogenic sounds and EMF all at once, or in succession, and acute or chronic in nature, is all unknown.

4.2. Future research

Currently, the sound sections in EIAs for various human activities show a lack of consideration for crustacean species. The knowledge gaps in noise and EMF research require addressing if EIAs are to be effective. In order to collect useful data for EIAs and to determine whether regulatory criteria are needed for the impacts of anthropogenic noise and EMF on crustacean species, the following is required:

- **Standardisation of experimental design**[72] perhaps encompassing a combination of field, caged, and laboratory-based studies (in order to overcome the difficulties associated with each method[8,13,27,74,155])
- **Evaluation of relevant sound components** (i.e. particle motion) that influence crustaceans, with the aim of developing an understanding of the detection ranges of individual species within these parameters[67,72,73,156–158]
- Increase the **understanding of different types of anthropogenic noise sources**
- **Realistic EMF strengths** from standardised field measurements
- **Noise and EMF multi-stressor experiments with real world timescales and levels** in order to gain an understanding of the multi-stressor effect model (additive, simple

comparative, multiplicative) and type of interaction (e.g. additive, synergistic, antagonistic) noise and EMF may have on crustaceans[159,160]

- **Species specific research** on commercially important species, or a broader range of species, contexts, locations, etc. to allow for possible cross-species predictions[67,161]
- **Long term studies**, considering response duration, recovery time, adaptation, and possible population level effects[67,154,159,162]
- **Identification of most vulnerable groups** within a population of the same species, in order to draw conclusions for the population level sensitivity[161] (e.g. whether berried ["pregnant"] females are more susceptible to anthropogenic sound than un-berried females, whether larger or smaller individuals are affected to a greater extent, whether the development and early larval stages are affected, etc.[163])
- Identify whether populations are potentially always vulnerable or whether particular **spatial or temporal factors** may dictate times or areas of higher sensitivity[70]
- **A mechanistic, integrative approach**, considering behavioural changes along with their physiological and genetic bases[154]
- **MRED monitoring** with adequate baseline and controls, and data made publicly available[164]

It is only with a greater comprehension of the underlying mechanisms of how noise and EMF act on physiological and ecological processes of crustaceans and the wider ecosystem that an understanding of the possible multi-stressor effects with be gained[159,165–167] and predictions can be developed for management and mitigation[154].

Potential means of filling existing knowledge gaps have been postulated by numerous groups. For example, Miller et al.[168] have demonstrated provisionally the use of modelling pile driving ranges of influence. Three different types of waves omitted from pile driving strikes were modelled in order to ascertain detection ranges of crustaceans and groundfish. They concluded that the reported levels of exposure influencing American lobster[17] could be found up to 500 m from the pile driving site, but stressed the complex reality of the situation. In addition, they estimated the particle velocity associated with pile driving out to 400 m from the site, which would be valuable knowledge for research into potential impacts on crustaceans[168].

Another possible methodology could be the use of passive acoustic monitoring (historically used for cetaceans). This has been proposed to be of potential benefit to noise-related research in crustaceans as it can identify overlaps between natural crustacean-borne noise and anthropogenic sounds, as well as an aid for monitoring purposes[71]. Research within this area will be species specific.

Hawkins & Popper[72] postulate the application of the Population Consequences of Acoustic Disturbance model (PCAD) to crustaceans, a procedure for assessing the influence of sound, which has been applied to marine mammals and one example of fish. The development of such criteria, or use of other models, may be able to help inform potential protection measures, such as those currently existing for marine mammals (e.g. noise limits for activities, exclusion zones which dictate that such animals cannot be within a certain radius of the activity), as well as the testing of existing marine mammal mitigation methods (Table 3), or the development of new ideas[157,169] for crustaceans, if required. To use a PCAD model the following information is required[170]:

- Characterise relevant acoustic signals.
- Describe resulting physical, physiological or behavioural changes.
- Determine any life functions or essential activities that are affected.
- Investigate change in vital rates that will impact populations.
- Examine population impacts which affect subsequent generations.

Côté et al.[159] note the practicality of reducing levels of stressors instead of completely removing a single stressor. Depending on the type of interaction, the reduction of local stressors can be extremely beneficial for local ecosystems when concurrently faced with global stressors, that are more difficult for local policy makers to control[150,159,160,171–174].

Until future research fills in current knowledge gaps to better understand how noise and EMF may affect UK commercially important species no crustacean specific mitigation recommendations can be made. Some of the noise mitigation methods used for marine mammals (Table 3) may inadvertently minimise potential impacts on crustaceans, but no work has been done in this area with regards to crustaceans. Results from noise research on crustaceans are extremely mixed and little has been conducted on particle motion; therefore, suggested mitigation methods could be unnecessary, ineffective, or impractical. For example, stopping wind farm construction during the larval development of all crustaceans could leave a very small window of opportunity to install any MREDs. Female European lobsters can be berried from early autumn until summer[175], and it is unknown what levels of particle motion, if any, have an effect on larval development and subsequent population numbers. This type of biological information for local species needs to be discussed for specific proposed MRED sites within EIAs. Certain mitigation methods used for marine mammals will not be effective for crustaceans; for example, those based on visual observations of the sea surface, such as those carried out by marine mammal observers, to detect presence of animals used to then advise survey/construction activities will be ineffective for detecting crustaceans (i.e. small animals that live on the seabed).

Similarly, until there is an understanding of what EMF strengths affect UK commercially important species, a specific amount of cable shielding cannot be recommended, as ‘safe’ levels are unknown. To date the only industry standard technique for reducing EMF emissions on the seabed is to bury the cable[176]. This technique, however, does not change the EMF in terms of field size or strength; it simply relocates it further within the benthos, thus reducing the detectable field on the seafloor. Cable burials are dependent upon substrate type, seafloor topography, and distance the cable will travel, in addition to any regulations within protected areas it may pass through. Cables are typically buried between 30 cm and 3 m. The lack of studies identifying the true effects of burying the cable hinders the conclusions that can be drawn about impact mitigation, particularly on benthos dwelling crustaceans.

Table 3. Summary of mitigation measures used to minimise potential effects of anthropogenic noise on marine mammals and information required to effectively implement mitigation measures. Information taken from reviews and reports[72,157,169,177–180].

The animals		**The sound**	
Species specific research on effects of stressors	• Response to exposure (e.g. behavioural, physiological, and genetic) • Duration of response • Adaptation • Consequence to population	**Comprehensive numerical model of sound fields**	Specific and relevant sound characteristics and how it/they will spread in the environment
Biological information to minimise effect	Identify: • Critical habitat • Migration routes • Reproductive periods • Sensitive life stages	**Changes to sound source to minimise effect**	Reducing unwanted and damaging sound or setting noise criteria • May be specific aspects of the sound only (e.g. level, duration, duty cycle, etc or particle motion for crustaceans) • Changes to propeller or other aspects of propulsion system • Activity reductions (e.g. fewer larger vessels or turbines)
			Alternative sound sources • Hydraulic pile driving instead of impulsive pile driving • BLUE piling technology (www.ihciqip.com)

			Sound shielding technology • Plastic wrapping • Bubble curtains • May not be effective in many instances (i.e. short piles or shallow water only)
			Aversive techniques • Ramp-up • Soft-start • Acoustic Deterrent Device (ADD)
			Safety zones • Visual sightings • Passive acoustic monitoring • Active acoustic monitoring

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Appendix 1 – Further background material

A1.1 Noise

Sound is produced as a wave, which has many characteristics that may have different effects on animals. For example, some animals may be sensitive to the frequency of a sound (i.e. its pitch), whereas others may be more sensitive to pressure levels (i.e. loudness), rise time (i.e. how quickly the sound reaches its maximum pressure), or the particle motion component of the sound wave[70]. Particle motion, in which water particles move or oscillate around a sound wave, can be detected by some animals via the physical movement of the particles[74]. As particles move areas of low and high pressure are created (Figure A1). Sound Pressure Level (SPL) is a measure of sound which defines the change in pressure associated with a sound wave, and can be a causative factor of physical acoustic trauma[72]. Particle motion is proportionally higher than SPLs at the source of a sound (called the "near field" or source level), but with increasing distance from the source (called the "far field"), the particle motion becomes equal with the sound pressure[73]. Examples of anthropogenic noise source levels are shown in Table A1. Another characteristic includes, Sound Exposure Level (SEL), which refers to the energy given out by an acoustic source and takes into account both the received level and the duration of the noise exposure[70,181]. SEL can be useful when relating sound exposures of different durations.

Vibrations, on the other hand, are formed by activities involving direct contact with the seabed, such as pile driving for windfarm construction.

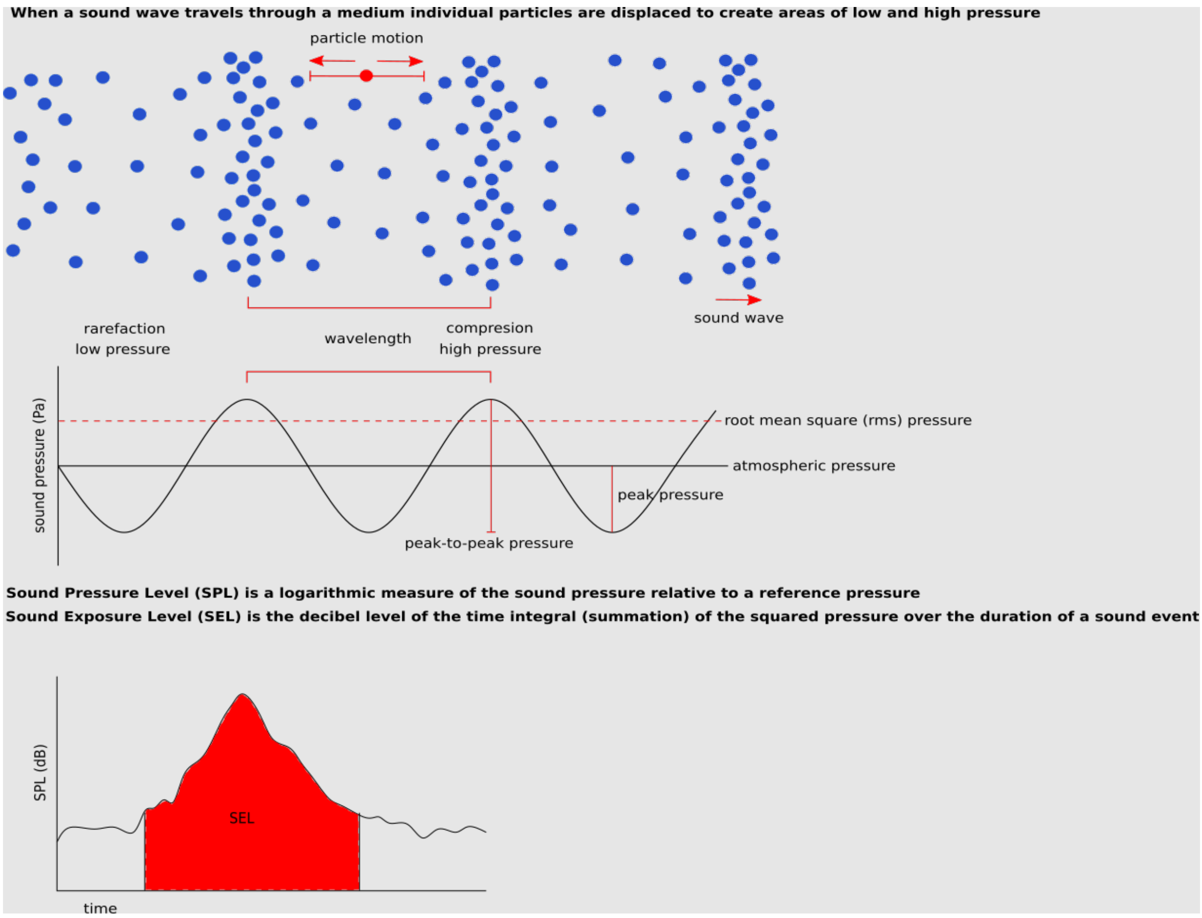

Figure A8. Simplified illustration of particle motion and sound pressure measurements.

Table A1. Overview of the acoustic properties of some anthropogenic sounds (modified from OSPAR report 2009[169]). p-to-p = peak-to-peak, rms = Root Mean Square, *Nominal source, **Higher source levels from drill ships use of bow thrusters, ***Projection based on literature data levels back-calculated at 1 m

Sound source	Source level (dB re 1 µPa-m)*	Frequency (Hz)	Major amplitude (Hz)	Duration (ms)	References
Offshore construction					
TNT (1-100 lbs)	272–287 peak	10–1,000	6 – 21	~1–10	Hildebrand 2004[182], OSPAR 2009[169]
Pile driving	215- >250	100–>20,000	100 – 500	10–100	Bailey et al. 2010[183], Nedwell & Howell 2004[114], OSPAR 2009[169], Thomsen et al. 2006[125]
Offshore industrial activities					
Oil & gas production activities	195		40–100		Hildebrand 2004[182]
Dredging	168–186 rms 150–185	20– >20,000	100 – 500	continuous	Greene & Moore 1995[184], Nedwell & Howell 2004[114], OSPAR 2009[169]
Drilling	145–190 rms**	10–10,000	< 100	continuous	Greene & Moore 1995[184], OSPAR 2009[169]
Tidal and wave energy devices***	165–175 rms***	10–50,000	-	continuous	OSPAR 2009[169]
Wind turbine	123–153	16–1,250 (up to 20,000)	30–200	continuous	Nedwell & Howell 2004[114], OSPAR 2009[169], Thomsen et al. 2006[125]
Shipping					
Small boats and ships	130–170	20– > 10,000	> 1,000	continuous	Greene & Moore 1995[184], Hildebrand 2004[182], Nedwell & Howell 2004[114], OSPAR 2009[169]
Large vessels	180–190 rms 198	5–500 (up to > 30,000)	> 200	continuous	Hildebrand 2004[182], OSPAR 2009[169]
Military sonar					
Military sonar low frequency	215–235 peak	100–500 (< 1,000)	-	600–1,000	Hildebrand 2004[182], OSPAR 2009[169]
Military sonar mid frequency	223–235 peak	1,000–20,000	3,500	500–2,000	Hildebrand 2004[182], OSPAR 2009[169]
Oil & gas seismic surveys					
Airgun array	> 250	5–300 (up to 100,000)	10–120	30–60	Greene & Moore 1995[184], Hildebrand 2004[182]
Other sonars and geophysical surveys					
Sub-bottom profiler	200–230 rms	400–30,000		0.1–160	Greene & Moore 1995[184]
Side scan	220–230 rms	50,000–500,000		0.01–0.1	Greene & Moore 1995[184]
Multibeam (echosounder hull-mounted)	235	12,000 peak		20	Hildebrand 2004[182]

Echosounders	235 peak	variable	variable 1,500–36,000	5–10	Hildebrand 2004[182], OSPAR 2009[169]
Research sonar	195	75–250 peak		120 s–20 minutes	Hildebrand 2004[182]
Navigation (transponder)	180–200 rms	7,000–60,000		3-40	Greene & Moore 1995[184]
Depth sounder	> 180 rms	> 12,000			Greene & Moore 1995[184]
Other					
Acoustic deterrent / harassment devices	130–200	5,000–160,000	5,000–30,000	2–2,000	Hildebrand 2004[182], OSPAR 2009[169]

The distance in which a sound wave propagates through water is influenced by various conditions, which means that the distance travelled, and the levels detected by organisms, differs on a site-by-site basis. For example, factors such as substrate type, temperature, and salinity (and associated changes in water density) can cause sound waves to travel different distances due to absorption, reflection, or refraction of the sound waves[66,74,181]. In addition, the manner in which an anthropogenic activity itself is carried out can dictate the noise levels produced, such as pile driving noise being dependent on the size and material of the pile and hammer, and the type of substrate the pile is being driven into[67].

In general, high amplitude, low frequency noises are likely the most important source of noise from a pollution perspective, as such noises are able to travel over large distances[67]. Additionally, impulsive noise is considered to be more damaging than continuous noise because it causes a rapid and irregular change in the local soundscape, pressure, and particle movement[18,67].

The research into crustacean sensitivities to noise and Vibration are summarised in Table A2 and vibration Table A3, respectively.

Table A2. Summary of reported acoustic sensitivities in marine crustaceans

Species	Tested frequency range	Summarised results / Comments	Reference
Norway lobster *(Nephrops norvegicus)*	20-300 Hz	Behavioural response between 20-200 Hz, no response over 200 Hz	Goodall et al. 1990[185]
Ghost crab *(Ocypode* spp.*)*	800-3000 Hz	Maximum sensitivity in 1000-2000 Hz	Horch 1971[186]
Paddle crab *(Ovalipes catharus)*	80-2000 Hz	Higher sensitivity in lower (80, 100 Hz) and higher (2000 Hz) frequencies	Radford et al. 2016[187]
Common prawn *(Palaemon serratus)*	100-3000 Hz	Sensitivity declining from 100 Hz	Lovell et al. 2005[188]
Mud crab *(Panopeus* spp.*)*	75-1600 Hz	Maximum sensitivity at 75 Hz and decreasing	Hughes et al. 2014[189]
Sand fiddler crab *(Uca pugilator)*	30-5000 Hz	Higher sensitivity at 30-60, 600 and 1.5 Hz	Salmon 1971[190]
Mudflat fiddler crab *(Uca rapax)*	30.5000 Hz	Higher sensitivity at 30, 480-1500, 5000 Hz	Salmon 1971[190]

Table A3. Overview of some thresholds of sensitivity to vibration in crustacean species. Modified from two existing papers[31,191].

Species (common and scientific names)	Sensitivity threshold (ms^{-2})	Frequency (Hz)
Shore crab (*Carcinus maenas*)	0.0002	20; 100-130
Common or brown shrimp (*Crangon crangon*)	0.4	20-200
	0.81	170
American lobster (*Homarus americanus*)	0.0002	75
Norway lobster (*Nephrops norvegicus*)	0.01-1.4	20-300
Horned ghost crab (*Ocypode ceratophthalmus*)	0.12	400
European hermit crab (*Pagurus bernhardus*)	0.11	5-410
Mud crab species (*Panopeus* spp.)	0.001	75-1600
Red-jointed fiddler crab (*Uca minax*)	0.0175	50
Sand fiddler crab (*Uca pugilator*)	0.005	20
	0.067	400
	0.04	30
Mudflat fiddler crab (*Uca rapax*)	0.06	60

A1.2 EMF

EMFs, consisting of an electric field (E-field) and magnetic field (B-field), are generated by a current flowing through a cable with the resultant field strength subject to many factors including[75,192]:

- Voltage
- Distance between conductors
- Cable type
- Current type
- Insulation/armouring type

Currently there is no industry standard insulation that can successfully shield both E-field and B-field emissions[51]. Where there is B-field leakage within standard cable configurations, an induced EMF (iEMF)[51] results. These could potentially cover large areas of the seabed around MRED deployment boundaries, depending on the scale and the number of cables used in a certain area. The resultant iEMF will be affected by saltwater ion movement via underwater currents near cables as well as the current type and strength passing through, which will result in an EMF of variable size and strength that is extremely hard to predict[193]. Normandeau Associates Inc. et al.[193] reported a great variation of EMF strengths around different structures associated with MREDs, whilst Thomsen et al.[194] reported higher EMF strengths around export cables, which in recent years utilise HVDC cables rather than inter-device cables typically consisting of AC. A review of the literature indicates that the current knowledge on EMF strengths emitted from MREDs is insufficient to allow for an informed assessment[195].

EMF strength is measured in Tesla (T) and subsequent derivations thereof, with 1 T = 1,000 mT = 1 x 10^6 µT. EMF strengths reported in the literature vary from 0.14 to 8.02 mT[59,193,196] with values used in scientific studies ranging from 2.8 to 165 mT[38,43,59,109,197]. Currents of around 450 to 1,600 Amperes (A) (AC 715A [33 kV cable] – 525 A [220 kV cable])[198] are found in undersea power cables resulting in EMF emissions of 3.2 mT in a perfect wire[196]. It has been shown in models that the strength of an EMF diminishes the further it travels from the source cable[198], whereby 220 kV cables produce a 22 µT magnetic field at source that falls to 2 µT 5 m away from the cable. Similarly, a 33 kV cable produces a 13 µT field that falls to 0.5/1 µT 5 m away from the source[198]. Bochert and Zettler[196] also highlighted the change in a 1,600 A cable diminishing from 3.2 mT at the cable surface to 0.32 mT and 0.11 mT at 1 m and 4 m, respectively. The unpredictability, and difficulty in assessing the true EMF, particularly the iEMF, around MREDs makes it difficult to determine the potential effects on marine life. EIAs for MREDs are based upon current scientific knowledge which is significantly lacking regarding the effects of EMF on marine invertebrates. A summary of EMF strengths used or reported in the literature is shown in Table A4.

Table A4. Underwater cable Electromagnetic Field (EMF) strengths used or reported in the literature.

EMF strength						**Source type and reference**
Modelled		**Measured**		**Experimental**		
AC	**DC**	**AC**	**DC**	**AC**	**DC**	
-	-	-	-	-	2.8 mT 40 mT	Scientific article Scott et al. 2018[38]
-	3.2 mT	-	-	-	3.7 mT	Scientific article Bochert & Zettler 2006[196]
18 µT	275 µT	-	-	165 mT	36 mT	Scientific article Cada et al. 2011[59]
-	0.4-8 mT	-	-	-	3 mT	Report Woodruff et al. 2012[43]
-	-	-	-	0.1-4.2 mT	0.1-4.2 mT	Scientific article Formicki et al. 2004[197]
0.9-1.5 µT	-	-	-	-	-	Report Gill & Bartlett 2011[199]
-	-	46.2-80 µT	-	46.2-80 µT	-	Scientific article Love et al. 2015[104]
-	-	-	-	1 mT	10 mT	Scientific article Fey et al. 2020[200]
51-66 µT	-	0.005-3.1 µT	51.3-72 µT	-	-	Report Hutchison et al. 2018[108]

A1.3 Multi-stressors

The broad interaction types mentioned in section 1.4 Multi-stressors, additive, synergistic, and antagonistic, most often fall under the additive effects model for defining and comparing effects of multiple stressors, and involves summing the effects of individual stressors together to give a cumulative outcome. The additive effects model is the multi-stressor model used most commonly in the scientific community[87,91]. There is; however, some debate around this model choice, and instances of when other models are more appropriate, for example, when mortality is the measured response a multiplicative model should be used[159,201–203].

With the additive effects model, an additive effect occurs when the total level of the effects is equal to the sum of the individual effects. With a synergistic effect, the total effect is greater than the sum of individual effects, i.e. greater than the additive effect. An antagonistic effect is less than the sum of individual effects, i.e. less than the additive effect. Piggott et al.[204] expanded these terms to include different directional effects (i.e. positive, negative, and neutral) (Table A5).

In the case of mortality an organism cannot die from one stressor if it has already died from a previous stressor. A multiplicative effect model is therefore used to describe competitive interactions where one stressor can be further operated on probabilistically by another stressor, and the maximum effect cannot be greater than 100% (e.g. $A + B - (A \times B)$)[91,159,202].

A third model, the simple comparative effects model, is used when the resulting effect of multiple stressors is equal to a single dominant stressor[91,205]. Jackson et al. [206] thought this model may be an explanation for the widespread antagonistic interactions seen in their meta-analysis of freshwater systems. Results from multiplicative effect models are also less than additive models, and are therefore also at risk at being misclassified as antagonistic interactions[159].

Table A5. Directional interaction classification used by Piggott et al.[204] that includes both magnitude and direction of the cumulative effect of multiple stressors. A = antagonistic, S = synergistic.

Classification	**Definition**	**Example**
Additive effect	Sum of individual effects	$+1 + 1 = 2$ $-1 + -1 = -2$ $-1 + 1 = 0$
Positive antagonistic	Less positive than predicted additively	$+1 + 1 = 0 < (+A) < 2$ $-1 + 1 = -1 \leq (+A) < 0$
Negative antagonistic	Less negative than predicted additively	$-1 + -1 = -2 < (-A) < 0$ $-1 + 1 = 1 < (-A) \leq 1$
Positive synergistic	More positive than predicted additively	$+1 + 1 = (+S) > 2$ $-1 + -1 = (+S) > 0$ $-1 + 1 = (+S) > 1$
Negative synergistic	More negative than predicted additively	$+1 + 1 = (-S) < 0$ $-1 + -1 = (-S) < -2$ $-1 + 1 = (-S) < -1$
Mitigating synergism	Completely opposite to cumulative effect	$+1 + 1 = -2$ $-1 + -1 = 2$

Meta-analyses, which include invertebrates, by Crain et al.[87] and Przeslawski et al.[89] revealed that multi-stressor studies in marine systems resulted in all three interaction types, with a significant synergistic overall interaction effect. The synergistic interaction became more negative when looking only at heterotrophs[87]; therefore, it may be more likely that crustaceans exposed to multi-stressors may respond in this way. Przeslawski et al.[89] found that arthropod embryos/larvae were robust, and showed no overall negative effect from certain abiotic stressor combinations. Crain et al.[87] highlight the high variance in interaction types and the strong effect all factors have on the interaction type. Furthermore, Gunderson et al.[88] noted that the high number of synergistic interactions reported in the literature may be due to researchers most commonly exposing organisms to stressors simultaneously and constantly, which may not reflect real world situations.

How multiple stressors interact may also depend on the kind and number of stressors, with a third stressor possibly intensifying the interaction[87,150]. Other factors include the temporal nature of the stressors (simultaneous vs. consecutive, frequency, duration, etc.) and the intensity of each stressor[88,201,207,208]. The level of the effect of a stressor may also vary depending on the response variable measured and the chosen endpoint [e.g. 209]. The motility of organisms must also be taken into account, as mobile species may move away from a stressor[88].

With multiple stressors there is also the possibility of higher order interactions, where the stressors themselves interact with each other or species responses may be context dependant, have varying evolutionarily or ecologically derived tolerances, or have varying responses based on their community interactions[87,167,210]. Stress responses from larvae may also depend on parental history, maternal imprinting and investment, and biotic variables (e.g. food availability)[89]. Even with all these complications, the information gained from multi-stressor studies is valuable for management decisions, and may assist local communities cope with global stressors [e.g. 87,150,159,160,173,174,211–213].

Appendix 2 – Literature review methods

To determine the current state of knowledge of the effects of noise and EMF on crustaceans a comprehensive search of academic databases was conducted using Heriot-Watt University's Discovery database and Google.

Primary sources utilised include:

- Electronic databases and literature – Heriot-Watt Discovery grants access to over 48,000 journals and 230 online databases including Web of Science, Scopus, and ScienceDirect.
- Heriot-Watt University Library – The library consists of a vast range of teaching resources including books, journals, theses and dissertations, conference proceedings, e-books, and conference papers.
- Environmental Impact Assessments/Environmental Statements from Offshore Wind farms – EIAs/ESs available online or on request from developers.

A2.1 Noise searches

The number of results returned for each set of noise related search terms varied and are broken down in the following table (the two numbers in each cell represent the different numbers of papers returned with each additional search term). These numbers are total returns, which is not limited to relevant papers only. There is also some crossover between databases, which is not accounted for here.

Search term	Web of Science	Science Direct	Scopus
Marine noise + crustacean/invertebrate	30/79	2,178/3,894	40/93
Marine noise pollution + crustacean/invertebrate	9/16	883/1,544	11/30
Underwater noise + crustacean/invertebrate	22/41	556/864	21/41
Anthropogenic noise + crustacean/invertebrate	14/55	699/1,496	16/60
Marine anthropogenic noise + crustacean/invertebrate	10/32	617/1,138	12/35
Seismic survey + crustacean/invertebrate	4/16	679/1,290	7/14
Air gun + crustacean/invertebrate	2/11	439/783	1/7
Pile driving + crustacean/invertebrate	3/9	216/502	4/10
Construction noise + crustacean/invertebrate	2/10	857/2,047	1/15
Shipping noise + crustacean/invertebrate	3/16	298/532	3/9
Boat noise + crustacean/invertebrate	7/9	457/743	9/8
Harbour noise + crustacean/invertebrate	4/10	756/1,653	2/8

Search term	Web of Science	Science Direct	Scopus
Motor noise + crustacean/invertebrate	10/5	756/2,169	11/20
Sonar noise + crustacean/invertebrate	3/5	250/384	4/3
(Tidal) turbine noise + crustacean/invertebrate	2/4	109/213	1/4
Wind farm noise + crustacean/invertebrate	1/4	0/1	0/2
Marine vibration + crustacean/invertebrate	11/9	1,165/1,641	10/19
Marine vibration pollution + crustacean/invertebrate	1/1	329/475	1/1
Underwater vibration + crustacean/invertebrate	1/3	260/363	0/4
Anthropogenic vibration + crustacean/invertebrate	3/7	187/311	0/0
Marine anthropogenic vibration + crustacean/invertebrate	3/5	159/263	0/0
Pile driving vibration + crustacean/invertebrate	1/3	67/103	2/4
Construction vibration + crustacean/invertebrate	1/3	499/822	2/3
(Tidal) turbine vibration + crustacean/invertebrate	0/0	61/101	0/0
Wind farm vibration + crustacean/invertebrate	0/0	0/0	0/0

A total of 34 research papers that looked at the effects of noise and crustaceans were found (Appendix 3), with additional review papers analysing existing research (either on anthropogenic noise as a whole or on small sections of it [e.g. seismic surveying noise specifically], and on invertebrates as a whole or crustaceans only). Regulatory literature for anthropogenic sound (such as EIAs) were assessed and found not to address crustaceans at all. As such, scientific literature was the focus for the noise and vibration section of this report.

A2.2 EMF searches

These numbers are total returns, which is not limited to relevant papers only. There is also some crossover between databases, which is not accounted for here. In total, 21 publications studied the effects of EMF on crustaceans (Appendix 4).

Search term	Web of Science	ScienceDirect	Scopus
MRED	196	177	719
EMF	29,555	20,508	29,048
Electromagnetic Field renewable energy	337	260	7,329
EMF MRED	3	2	10
EMF subsea cable	6	4	37

EMF wind farm	12	14	336
EMF offshore	17	25	467
EMF invertebrate	7 (1 relevant)	208	12 (1 relevant)
EMF crustacean	2 (1 marine, 1 freshwater)	97	5
EMF crab	4 (3 relevant)	164	4 (3 relevant)
EMF lobster	2	74	2 (not relevant, neurology)
EMF prawn	0	14	0

A2.3 Multi-stressor searches

There are no published multi-stressor studies on potential combined effects of noise and EMF exposure on crustaceans.

Search term	Web of Science	ScienceDirect	Scopus
Multi-stressor noise	2 (not relevant, helicopters or rats)	52,558	13 (not relevant)
Multi-stressor noise crustacean	-	10 (not relevant)	-
Multi-stressor crab	-	4 (not relevant)	-
Multi-stressor lobster	-	4 (not relevant)	-
Multi-stressor prawn	-	2 (not relevant)	-
Multi-stressor EMF or Electromagnetic Field	0	3 (not relevant)	0
Noise EMF invertebrate	1 (not multi-stressor)	66	2 (not multi-stressor or neurology)
Noise EMF crustacean	0	38	0
Noise EMF crab	2 (not multi-stressor or not relevant)	57	1 (not relevant)
Noise EMF lobster	0	36	0
Noise EMF prawn	0	6 (not multi-stressor or not relevant)	0

Further multi-stressor resources or searches included:

- Colleagues studying noise multi-stressors on crustaceans
- Searches in cited literature
- Google searches
    - (Multi-stressor) AND (crustacean OR lobster OR crab OR prawn OR invertebrate) AND (noise OR EMF)

Appendix 3 – Anthropogenic noise & crustacean research

A summary of the existing 34 papers on the influence of anthropogenic noise on crustacean species is provided in the following table. UK commercially important species are highlighted in dark grey and species within the same family (i.e. Cancridea, Crangonidae, Nephropidea, or Palinuridae) as UK commercially important species are highlighted in light grey.

Species	Noise/vibration type(s) and level(s)	Effect(s) of stressor	Parameter(s) measured	Reference
Snapping shrimp (*Alpheus glaber, Alpheus macrocheles, Athanas nitescens*)	Simulated pile driving, bursts of three peak-to-peak (p-p) SPLs: High = 152 dB re 1 µPa p-p; Medium = 145 ± 1.06 dB re 1 µPa p-p Low = 137 ± 1.71 dB re 1 µPa p-p	Change (increase) to natural snapping "chorus" for all species	Snap number and amplitude	Spiga 2016[10]
Tunneling mud crab (*Austrohelice crassa*), Hairy-handed crab (*Hemigrapsus crenulatus*)	Sound emitted from underwater tidal turbine and offshore wind turbine Tidal = 125 or 145 or dB re 1 µPa Wind = 145 dB re 1 µPa Most of the energy was in the frequency band < 1 kHz	Delayed larval development for both species (time to metamorphosis stage)	Median time to metamorphosis	Pine et al. 2012[5]
Striped barnacle (*Balanus amphitrite*)	Use of the Hydro-Sonic Hull tender (a ship anti-fouling device) 3x frequency levels:15, 30, 45 Hz	Possible inhibition of an early stage of development (metamorphosis) and attachment	Counting of attached vs unattached cyprid (earlier stage of development) and metamorphosised juvenile (later stage) barnacles	Branscomb & Rittschof 1984[1]
Dungeness crab (*Cancer magister* now accepted as *Metacarcinus magister*)	Seismic air gun 13.8-litre array of 7 air guns of mixed sizes, at 3 distances (1, 3 and 10m) 1 m: SPL (p-p): 230.9 dB re 1 µPa p-p Rise time: 4.9 msec Maximum cumulative energy density: 250.7 J/m^2 Cumulative energy density at time of maximum positive	No effect on larval development or mortality	Immediate mortality, survival to molt to Stage III and Stage IV, time to molt to Stages III and IV	Pearson et al. 1994[4]

Species	Noise/vibration type(s) and level(s)	Effect(s) of stressor	Parameter(s) measured	Reference
	pressure: 82.9 J/m^2 Average intensity during rise time: 17.5 kW/m^2 Maximum intensity during pulse passage: 64.4 kW/m^2 3 m: SPL (p-p): 229.1 dB re 1 µPa p-p Rise time: 5.7 msec Maximum cumulative energy density: 172.2 J/m^2 Cumulative energy density at time of maximum positive pressure: 67.6 J/m^2 Average intensity during rise time: 12.6 kW/m^2 Maximum intensity during pulse passage: 42.9 kW/m^2 10m: SPL (p-p): 230.9 dB re 1 µPa p-p Rise time: 4.9 msec Maximum cumulative energy density: 250.7 J/m^2 Cumulative energy density at time of maximum positive pressure: 82.9 J/m^2 Average intensity during rise time: 17.5 kW/m^2 Maximum intensity during pulse passage: 64.4 kW/m^2			
European green crab (*Carcinus maenas*), Brown shrimp (*Crangon crangon*)	Broadband artificial “white noise” SPL: 129.5–142.0 dB re 1 µPa	*C. maenas*: Reduced foraging behaviour, no effect on feeding rate *C.* crangon: Increased foraging behaviour, no effect on feeding rate	Accumulation of individuals aggregated at a food item (cumulative count), individuals feeding at given timepoints (feeding rate)	Hubert et al. 2018[21]

Shore crab (*Carcinus maenas*)	Single and repeated exposure ship-noise playback 148–155 dB rms re 1 µPa	Size-dependent increase in metabolic rate and potentially greater stress in single ship-noise playback	Oxygen consumption	Wale et al. 2013[25]
	Ship noise tracks 148–155 dB rms re 1 µPa for ship noise	Disrupted feeding behaviour, slower anti-predator response, faster righting time	Time to locate food source Disruption of feeding once feeding has started (i.e. cessation) Time to retreat to shelter during simulated predatory attack Righting time	Wale et al. 2013[22]
Snow crab (*Chionoecetes opilio*)	Seismic surveys Single array 40-in^3 (0.65 l): peak broadband sound levels 201– 227 dB re 1 µPa, energy densities of 183–187 dB re 1 µPa^2/Hz, frequency range 24–31 Hz Multi-gun array (7 guns, 200 in^3 [0.33 l]): 197–237 dB re 1 µPa, maximum energy density of 175 dB re 1 µPa^2/Hz, frequency range 17–19 Hz	Stunted egg development No significant effect on: catch rate, immediate or delayed mortality, effects on haemolymph or organs (even in animals exposed to seismic source at very close range)	Developmental differences between control eggs and eggs exposed to air guns Crab catch rate, survival, haemolymph chemistry, organ and tissue pathology (hepatopancreas and heart)	Christian et al. 2003[12]
	Operational seismic survey (132 hr survey time, 1,310 in^3 air-gun array) No noise characteristic specifics given	Short term: gills, antennules and statocysts were “soiled” with sediment, but were completely clean when sampled 5 months later No significant effect on: internal organs (changes seen could not be attributed to seismic surveys), immediate or mid-term mortality,	Morphology of gills and internal organs, mortality, feeding behaviour, embryo survival to hatch rate, larval swimming behaviour	DFO 2004[3]

		feeding behaviours, embryo survival or post-hatching movement		
	2 years of seismic surveys (2015 and 2016) Both 2015 and 2016: airgun array 4,880 in^3 (80 l). “Airgun Array Sound Model” used to model the noise levels: zero-to-peak SPL = 251 dB re 1 µPa @ 1 m source sound exposure level = 229 dB re 1 µPa^2.s @ 1 m	No effect on short- or long-term catch rates (days or weeks), limited long-term effects on survival	Catch rate, survival rate over 18 months	Morris et al. 2018[27]
Caribbean hermit crab (*Coenobita clypeatus*)	Boat motor playback 98.1 ± 2.6 (SD) dB SPL (measured 1 m from speaker)	Reduced predator risk assessment	Time to predator avoidance behaviour: distance at which first response was seen, distance at which individuals began hiding behaviour	Chan et al. 2010[29]
Brown shrimp (*Crangon crangon*)	High noise levels mimicking working aquarium 30 dB in 25–400 Hz frequency range Peak sound pressure at between 25–30 dB//µbar/Hz	Reduction in growth and reproduction rates	Mean total length, weight, percentage of egg-carrying females over time (time to ovogenesis [development of eggs]), spawning (time to spawning, ability to spawn multiple times)	Lagardère 1982[23] (France)
	Animals were placed in tanks surrounded by the noise of a working aquarium vs. animals in soundproofed tanks In all frequency bands, sound pressure was as follows: Working aquarium: +25 dB µbar^{-1} Soundproofing: -4 dB µbar^{-1} In the specific frequency band of 0–1 kHz: Working aquarium: approximately + 5 µbar^{-1} Hz^{-1} Soundproofing: a little under approximately -20 dB µbar^{-1} Hz^{-1} Increase in sound pressure increment of 29 dB	Increased metabolic rate (oxygen consumption and ammonia excretion)	Ammonia excretion rate, oxygen consumption rate	Regnault & Lagardère 1983[24]

Antarctic krill (*Euphasia superba*)	Working research vessel noise compared an Autonomous Underwater Vehicle (AUV) Maximum difference between AUV and vessel noise was 50 dB at 520 Hz Maximum sound pressures were: Research vessel: a little under 150 dB re 1 µPa @ 1 m AUV: approximately 105 dB re 1 µPa @ 1 m	No avoidance behaviour	Density of krill along 7x transects (g m^{-2})	Brierley et al. 2003[32]
Southern brown shrimp (*Farfantepenaeus subtilis* now accepted as *Penaeus subtilis*), Southern white shrimp (*Litopenaeus schmitti* now accepted as *Penaeus schmitti*), Atlantic Seabob (*Xyphopenaeus kroyeri*)	Seismic air-guns, 635 in^3 (10.4 l) array Peak pressure of 196 dB re 1 µPa @ 1 m	No significant influence on population levels	Bottom trawl yields (before and after air-gun surveys)	Andriguetto-Filho et al. 2005[26]

American lobster (*Homarus americanus*)	Seismic air guns: 10 in^3 sleeve gun in the laboratory, 40 in^3 sleeve gun in the field Low-level exposure (carried out in the laboratory) = approximately 202 dB re 1 µPa p-p, energy density 144-169 dB re 1µPa^2/Hz High-level exposure (carried out in the field) = approximately 227 dB re 1 µPa p-p, average peak energy density 187 dB re 1µPa^2/Hz	Effects observed: increased food consumption, changes in haemolymph biochemistry; changes in hepatopancreas 4 months after exposure No effect on: immediate or delayed mortality, posture in the water (associated with mechanosensory systems)	Feeding rate, haemolymph biochemistry, study of hepatopancreatic cells Mortality (immediate and long-term), turnover rate	Payne et al. 2007[17]
Spiny lobster or Southern rock lobster (*Jasus edwardsii*)	Seismic survey, three airgun setups: 45 in^3: Maximum SPL = 209 dB re 1 µPa p-p Max. SEL = 186 dB re 1 µPa^2.s Max. cumulative SEL = 192 dB re 1 µPa^2.s (median cumulative SEL = 191) 150 in^3 low pressure: Max. SPL = 210 dB re 1 µPa p-p Max. SEL = 189 dB re 1 µPa^2.s Max. cumulative SEL = 193 dB re 1 µPa^2.s (median cumulative SEL = 192) 150 in^3 high pressure: Max. SPL = 212 dB re 1 µPa p-p Max. SEL = 190 dB re 1 µPa^2.s Max. cumulative SEL = 199 dB re 1 µPa^2.s (median cumulative SEL = 197)	No effect on fecundity, egg or larval development, or larval health	Mortality and egg bundle loss of female berried lobsters, larval hatch counts Larval abnormalities (morphology), mass and energy content (caloric content), competency of hatched larvae (survival under stress conditions - elevated temperature and reduced salinity)	Day et al. 2016[2]
	Seismic survey, three airgun setups:	Damage to statocyst, in turn impairing righting reflex	Righting time, statocyst morphology (observed using scanning electron	Day et al. 2019[13]

	45 in^3: Maximum SPL = 209 dB re 1 µPa p-p Source SEL = 200 dB re 1 µPa^2.s Max. cumulative SEL = 192 dB re 1 µPa^2.s (median cumulative SEL = 191) 150 in^3 low pressure (8.9 MPa) Max. SPL = 210 dB re 1 µPa p-p Source SEL = 203 dB re 1 µPa^2.s Max. cumulative SEL = 193 dB re 1 µPa^2.s (median cumulative SEL = 192) 150 in^3 high pressure (13.8 MPa) Max. SPL = 213 dB re 1 µPa p-p Source SEL = 205 dB re 1 µPa^2.s Max. cumulative SEL = 195 dB re 1 µPa^2.s (median cumulative SEL = 192)		microscopy). Both short-term and long-term effects monitored	
	Seismic air gun exposures Experiment 1: egg-laden females, 0.74L air gun @ 13.8 MPa (2000 psi) Max. cumulative SEL 192 dB re 1 µPa^2.s (with median cumulative SEL = 191) Max. single shot peak exposure: 209 dB re 1 µPa p-p Max. single shot SEL: 186 dB re 1 µPa^2.s Experiment 2: egg-laden females, 2.46: air gun @ 8.96 MPa Max. cumulative SEL 193 dB re 1 µPa^2.s (with median cumulative SEL = 192) Max. single shot peak exposure: 210 dB re 1 µPa p-p	Chronic influences the immune system (study found both suppression and elevation) No effect on other haematological parameters or hepatopancreas weight	Total Haemocyte Count (THC), haemolymph refractive index No influence on: other haemolymph biochemistry, hepatopancreas index, survival	Fitzgibbon et al. 2017[16]

	Max. single shot SEL: 189 dB re 1 µPa^2.s Experiment 3: non egg-laden females, 2.46L air gun @ 13.8 MPa Max. cumulative SEL 195 dB re 1 µPa^2.s (with median cumulative SEL = 192) Max. single shot peak exposure: 213 dB re 1 µPa p-p Max. single shot SEL: 191 dB re 1 µPa^2.s Experiment 4: males and egg-laden females (at 2x different points post-extrusion), 2.46 L air gun @ 13.8 MPa Max. cumulative SEL 197 dB re 1 µPa^2.s (with median cumulative SEL = 195) Max. single shot peak exposure: 209 dB re 1 µPa p-p Max. single shot SEL: 188 dB re 1 µPa^2.s			
Pacific white shrimp (*Litopenaeus vannamei* now accepted as *Penaeus vannamei*)	Pile driving noise, simulated by "drubbing" with a bamboo pole in a laboratory setting (this was deemed to have similar sound characteristics to pile driving with a 2 m steel pile within 200 m) Drubbing sound characteristics: Peak sound: 178 dB$_{peak}$ re 1 µPa Average peak frequency: 680 Hz	Significant increase in movement (moving away from noise source, gathering together and swimming towards the water surface)	Total movement trajectory and distances, movement speed	Zhou et al. 2016[19]
Neohelice granulata	Human lab-generated sweep tone intended to give bandwidth ranges comparable to most of the frequencies produced by human activities (continuous and impulsive) Ascending sweeps in a bandwidth range of 2.5–25 kHz Maximum SPL of all the sweeps was 136 dB re 1 µPa	Increased movement, alteration of acoustic behaviour, biochemical alterations	Locomotion (distance moved and velocity), acoustic behaviours (number of signals emitted), haemolymph biochemistry	Filiciotto et al. 2018[9]

Norway lobster (*Nephrops norvegicus*)	Broadband sound fields that resemble offshore shipping (Continuous Broadband Noise [CBN]) and construction activity (Impulsive Broadband Noise [IBN]) SPL for CBN generally in the region of 135-140 dB re 1 µPa SEL for IBN approximately 150 dB re 1 µPa^{2}s	Reduced burying and movement Increased bioirrigation No effect on tissue biochemistry	Sediment profiling image camera and fluorescent-dyed sediment particles, measured levels of an inert tracer (bromide) from the substrate in the water column movement Tissue glucose and lactate concentration	Solan et al. 2016[18]
Acadian hermit crab (*Pagurus acadianus*)	Impulsive noise similar to a pile driving “strike” Repetitive low-frequency pulses, peak energy in all 3 axes at 60 Hz, in the vertical axis at 400 Hz, with the bulk of energy at 500–700 Hz Average peak velocities: @ 1 m = 0.0005 m s^{-1}, 0.00001 m s^{-1} and 0.0001 m s^{-1} for CH1, 2 and 3 (specifically in the order of vertical first: y, x, z plane) @ 5 m = 0.00009 m s^{-1}, 0.00002 m s^{-1} and 0.00002 m s^{-1}	Fewer crabs attracted to a chemical cue after noise exposure	Number of crabs moving towards a highly attractive chemical cute (newly available shell home)	Roberts & Laidre 2019[33]
European common hermit crab (*Pagurus bernhardus*)	Shipping and boat noise Mean SPLs: Shipping noise: 58 dB re 1 µPa Boat noise: 50 dB re 1 µPa	Reduced predator awareness Not affected: predator response type, emergence time	Average time to first antipredator response, predator response type (freeze, flee, hide), time to emergence	Nousek-McGregor & Mei 2016[30]
	Sinusoidal vibrations of 8s duration were presented at 11 amplitudes (in increments of 6 dB) and 7 frequencies (5–410 Hz) Average sensitivities recorded between 0.11–0.29 m s^{-2} for indicator 1, and 0.09–0.44 m s^{-2} for indicator 2 (see “Parameter(s) measured” column)	Change in reception indicators with increasing vibration levels	Indicator 1: Movement of 2nd antenna Indicator 2: Onset/stopping of movement	Roberts et al. 2016[34]

	Simulated substrate-borne vibration due to pile driving, using a “staircase method” with increasing amplitudes and a range of frequencies. In total 11 amplitudes and 7 frequencies (5–400 Hz) were investigated Overall sensitivities recorded between 0.1–0.5 m/s^2, highest sensitivity reported at 0.1 m/s^2 at 10 Hz	Triggered antipredator behaviour, change in reception indicator	Retreat into shell (full or partial), antenna “sweep”	Roberts & Breithaupt 2016[31]
	Ship noise Average maximum SPL: 143.6 dB rms re 1 µPa	Studied a 3-way interaction to find, assess, and accept or reject an optimal shell (when in a shell 50 or 80% of optimal) with ship noise, and with or without a predator Ship noise alone removed the different behaviours seen by 50% and 80% individuals in response to optimal shell Ship noise plus predator reversed the decisions made by 50% and 80% individuals in response to optimal shell	Shell assessment behaviour, time to decision	Tidau & Briffa 2019[6]
	Shipping noise Average maximum SPL: 119.4 dB rms re 1 µPa	Study design: crabs in optimal or suboptimal shells, given the choice to remain alone in a neutral zone, or enter another 2 zones to group with 1 or 5 other crabs	Grouping preference (being with other crabs or alone)	Tidau & Briffa 2019[7]

		Shipping noise reversed grouping behaviour in crabs in optimal vs. suboptimal shells		
	General lab-generated “Anthropogenic noise”, Sound filtered above 2 kHz, played at approximately 165 dB re 1 v/µPa	Individuals in suboptimal shells offered optimal shells approached the shell faster, spent less time investigating it, entered it faster and took less time to make a final decision, but fewer crabs chose to take the optimal shell	Shell selection behaviour (time to contact shell, shell investigation, time to enter shell, final decision [whether or not to move into the optimal shell], time to final decision)	Walsh et al. 2017[8]
Common prawn (*Palaemon serratus*)	Shipping/boat noise Maximum SPL for shipping noise between approximately 135–140 dB re 1 µPa, frequency band 0.1–3 kHz (maximum background SPL for same band = 86 dB re 1 µPa)	Increased time resting, increased time outside of shelter, biochemical changes in haemolymph, increased gene expression in 2 of 4 measured genes in the brain	Movement patterns (walking and resting state), time inside vs. outside a shelter, biochemical parameters in haemolymph, expression of four genes for Heat Shock Proteins (HSPs) the brain	Filiciotto et al. 2016[15]
European/ Mediterranean spiny lobster (*Palinurus elephas*)	Shipping/boat noise Maximum mean SPL between approximately 100–125 dB re 1 µPa	Alteration to a range of biochemical parameters and increased gene expression potentially indicative of stress	Various haemolymph parameters, HSP gene expression	Celi et al. 2015[11]
	Boat noise Maximum mean SPL between approximately 100–125 dB re 1 µPa	Increased movement, alterations to haemolymph parameters and increased gene expression potentially indicative of stress	Movement (velocity, distance moved, mobility, moving values), haemolymph chemistry, HSP gene expression	Filiciotto et al. 2014[14]
Rock lobster (scientific name	Seismic discharges. Study looked at catch rates surrounding historic assays	No evidence of effect of seismic discharges on catch	Historic catch rates (catch per unit effort) before, during, and after historic	Parry & Gason 2006[28]

not provided)	No specific sound values were available, but differences in sound intensity between airgun arrays were estimated	rates	seismic surveys were performed	
Mud crab (*Scylla paramamosain*)	Sounds mimicking offshore anthropogenic activities 3x linear sweep levels: 163.8 dB re 1 µPa, 181.6 dB re 1 µPa, 197.4 dB re 1 µPa. Main energy was concentrated in the 600–800 Hz range	Highest noise group: Increased movement and expression of a gene which potentially indicates stress	Movement (average speed, total movement distance), HSP gene expression	Zhou et al. 2018[20]

Appendix 4 – EMF & crustacean research

A summary of the existing papers on the influence of EMF on crustacean species is provided in the following table. UK commercially important species are highlighted in dark grey and species within the same family (i.e. Cancridea, Crangonidae, Nephropidea, or Palinuridae) as UK commercially important species are highlighted in light grey.

		AC	**DC**	**Effects**					
Species	**Geographic location**	**Frequency (Hz), maximum flux density (mT)**	**flux density (mT)**	**Behavioural**	**Physiological**	**Development/ Early life stages**	**Fisheries**	**Study type**	**Reference**
Brine shrimp (*Artemia* sp.)	Europe	1 mHz and 36.64 GHz	25 mT	-	Yes	Yes		Lab	Shckorbatov et al. 2010[47]
Danube crayfish (*Astacus leptodactylus,* now accepted as *Pontastacus leptodactylus*)	Europe	0.001–100 Hz, 1–400 μT	-	-	Yes	-	-	Lab	Uzdensky & Kuyko 1997[48]
Freshwater crab (*Barytelphusa cunicularis*)	Asia	50 Hz strength NA	-	Yes	Yes	-	Yes	Lab	Rosaria & Martin 2010[37]
Edible crab (*Cancer pagurus*)	Europe	-	2.8 & 40 mT	Yes	Yes	-	Yes	Lab	Scott et al. 2018[38]
Common shore crab (*Carcinus maenas*)	Europe	type and strength NA		-	-	-	No	Field	Langhamer et al. 2016[147]
Brown shrimp/North Sea prawn (*Crangon crangon*), round crab (*Rhithropanopeus harrisii*), glacial relict isopod (*Saduria entomon*)	Europe	-	3.7 mT	-	No	-	-	Lab	Bochert & Zettler 2004[109]
American lobster (*Homarus americanus*)	North America	0.05–0.3 μT	0.0513–0.0653 mT	No	-	-	-	Field	Hutchison et al. 2018[108]
European lobster (*Homarus gammarus*)[105]	Europe	0.230 mT	0.230 mT	No	-	No	-	Lab	Taormina et al. 2020[105]
	Europe	500–1200	-	-	No	-	-	Lab	Ueno et al. 1986[107]

		mT							
Idotea baltica basteri	Europe	-	Earth zeroed	Yes	-	-	-	Lab	Ugolini & Pezzani 1995[42]
Rock crabs (*Metacarcinus anthonyi*), red rock crab (*Cancer productus*)	North America	0.05–0.08 mT type NA		No	-	-	No	Field	Love et al. 2015[104]
Dungeness crab (*Metacarcinus magister*)	North America	-	0.33–3.2 mT	Yes	-	-	-	Lab	Woodruff et al. 2012[43]
Dungeness crab (*Metacarcinus magister*), red rock crab (*Cancer productus*)	North America	NA	-	No	-	-	No	Field	Love et al. 2017[103]
Spinycheek crayfish (*Orconectes limosus* now accepted as *Faxonius limosus*)	Europe	-	0.19–0.8 mT	Yes	-	-	Yes	Field	Tański et al. 2005[39]
Caribbean spiny lobster (*Palinurus argus* now accepted as *Panulirus argus*)	North America	-	85 mT	Yes	-	-	-	Lab	Ernst & Lohmann 2016[35]
	North America	-	Earth	Yes	-	-	-	Field	Lohmann et al. 1995[36]
Red swamp cray fish (*Procambarus clarkii*)	Asia	-	35 mT	Yes	Yes	-	-	Lab	Yeh et al. 2008[45]
	Asia	-	4.74–43.45 mT	Yes	Yes	-	-	Lab	Ye et al. 2004[44]
Equatorial sandhopper (*Talorchestia martensii*)	Africa	-	Earth zeroed	Yes	-	-	-	Lab	Ugolini 2006[41]
	Africa	-	Earth zeroed	Yes	-	-	-	Lab	Ugolini 2001[40]
Fidler crabs (*Uca pugilator, Uca pugnax* now accepted as *Leptuca pugilator* and *Minuca pugnax*)	North America	-	10 mT	-	Yes	-	-	Lab	Lee & Weis 1980[46]

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About Us: Seafish is a non-departmental public body (NDPB), supporting the £10bn UK seafood industry from catch to plate. Our vision is for a seafood industry that is truly thriving and we use our unique position, right at the heart of industry, to work in partnership with businesses, Government and other stakeholders to make progress together.

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