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Review

Animal displacement from marine energy development: Mechanisms and consequences

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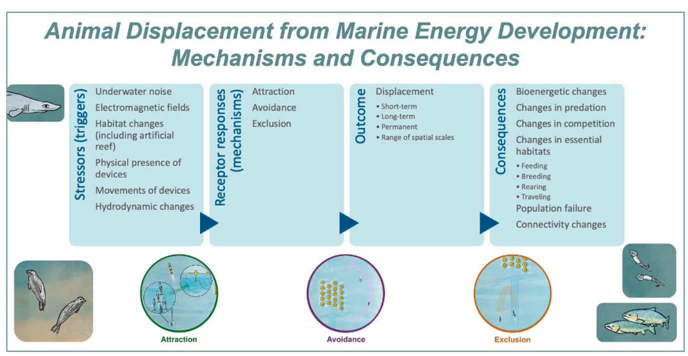
HIGHLIGHTS

- Large-scale marine energy projects may lead to displacement of animals.
- We provide clarity regarding definition, mechanisms, and effects of displacement.
- We define displacement as the outcome of either attraction, avoidance, or exclusion.
- Displacement is triggered by animals' response to stressors acting as a disturbance.
- Displacement can lead to consequences at the individual through population levels.

GRAPHICAL ABSTRACT



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ABSTRACT

For marine wave and tidal energy to successfully contribute to global renewable energy goals and climate change mitigation, marine energy projects need to expand beyond small deployments to large-scale arrays. However, with large-scale projects come potential environmental effects not observed at the scales of single devices and small arrays. One of these effects is the risk of displacing marine animals from their preferred habitats or their migration routes, which may increase with the size of arrays and location. Many marine animals may be susceptible to some level of displacement once large marine energy arrays are increasingly integrated into the seascape, including large migratory animals, non-migratory pelagic animals with large home ranges, and benthic and demersal mobile organisms with more limited ranges, among many others. Yet, research around the mechanisms and effects of displacement have been hindered by the lack of clarity within the international marine energy community regarding the definition of displacement, how it occurs, its consequences, species of concern,

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and methods to investigate the outcomes. This review paper leveraged lessons learned from other industries, such as offshore development, to establish a definition of displacement in the marine energy context, explore which functional groups of marine animals may be affected and in what way, and identify pathways for investigating displacement through modeling and monitoring. In the marine energy context, we defined displacement as the outcome of one of three mechanisms (i.e., attraction, avoidance, and exclusion) triggered by an animal's response to one or more stressors acting as a disturbance, with various consequences at the individual through population levels. The knowledge gaps highlighted in this study will help the regulatory and scientific communities prepare for mitigating, observing, measuring, and characterizing displacement of various animals around marine energy arrays in order to prevent irreversible consequences.

1. Introduction

Marine energy that harvests energy from waves, tides or other movement of water, will need to progress towards large-scale arrays for the sector to successfully contribute to national portfolios of renewable energy to mitigate global climate change. However, this growth must be accompanied by the investigation of potential environmental effects at scales larger than those of single devices. While a number of stressor-receptor interactions associated with marine energy have been identified (Copping et al., 2016; Copping and Hemery, 2020), not necessarily all of these interactions are relevant at the scale of small numbers of devices, such as changes in oceanographic systems and displacement of marine animals (Copping and Hemery, 2020). In the marine energy context, stressors are anthropogenic pressures relating to marine energy developments that can produce stress, harm, or injury to receptors such as marine animals or habitats, and oceanographic or ecosystem processes (Boehlert and Gill, 2010).

Whether large arrays of marine energy devices (i.e., 10–30 devices; Hasselman et al., 2023) will displace marine animals from their preferred or essential habitats remains to be examined (Copping et al., 2021). Many marine animals undertake annual migrations, during which they could encounter marine energy arrays, potentially altering course and lengthening their routes to avoid the devices. In jurisdictions without regulations protecting critical habitats, resident animals may also be displaced locally if a complete or partial loss of critical habitats occurs due to the installation and operation of arrays. However, research around mechanisms and effects of displacement has been hindered by the lack of large-scale deployed arrays (Buenau et al., 2022). In addition, there is a lack of clarity within the international marine energy community regarding the definition of displacement, the mechanisms that cause displacement, as well as the consequences, species of concern, and methods to investigate the outcomes.

This review paper aims to establish a definition of this stressor-receptor interaction, explore which groups of marine animals may be affected and in what way, and identifies pathways for investigating displacement through modeling and monitoring in the marine energy context. Since displacement of marine animals is not specific to the marine energy sector, lessons may be learned from research around other marine, or even terrestrial, human activities. Information from these activities that provides insight into displacement around marine energy devices needs to be identified. Remaining knowledge gaps will need to be filled through targeted research studies, involving field-based approaches and/or numerical modeling. To that effect, a literature review on displacement of marine animals was undertaken across three offshore energy sectors (i.e., marine energy, offshore wind, and oil and gas) as well as other anthropogenic activities that could potentially trigger wildlife displacement (e.g., shipping, land-based wind, or roads), and a workshop was organized with international subject matter experts to gather feedback and reach a consensus around the definition and mechanisms of displacement.

2. Information gathering

2.1. Literature review

Gathering of the literature on displacement was carried out with a keyword search in Scopus (www.scopus.com) and the Tethys knowledge base (www.tethys.pnnl.gov), targeting journal articles and reports published between January 2013 and February 2023 to keep the task manageable. Search terms are listed in Table 1 and were searched within article titles and abstracts. The review of the 940 documents resulting from the keyword search followed a two-step process: down-selection of the documents based on the relevance of their titles, leading to 132 documents; then refinement based on the relevance of the abstracts, leading to 87 articles. The thorough review of the remaining documents led to the addition of a handful more relevant publications that were missed during the keyword search, including key documents published prior to 2013. Relevance was defined as whether the content of a document provided a definition of animal displacement due to an anthropogenic activity (18 documents), a description of its mechanism and/or its consequences on individual animals and populations (72 documents), a description of methods of investigations (i.e., numerical models and field monitoring; 55 documents), background information (11 documents), and/or knowledge gaps (18 documents).

Table 1
Keywords used for the literature search in Scopus and Tethys. Search terms within each column were combined by "OR" whereas search terms from different columns were combined with the "AND".

Technologies	Mechanisms	Receptors
"tidal energy" OR "wave energy" OR "ocean current energy" OR "marine current energy" OR "OTEC" OR "ocean thermal energy conver*" OR "marine energy" OR "marine renewable" OR "ocean energy" OR "ocean renewable" OR ("marine" W/10 "hydrokinetic") OR "MHK" OR "offshore renewable energy" or "offshore energy" OR "aquaculture" OR "oil and gas" OR "offshore wind" OR "shipping" OR "navigation" OR "communication cable" OR "land-based wind" OR ("road*" W/10 "crossing") OR "wildlife corridor" OR ("fence" W/10 "field") OR ("fence" W/10 "garden") OR "military testing range" OR "marine protected area"	"displacement" OR "avoidance" OR "disturbance" OR "attraction" OR "migrat* route"	"cetacean" OR "whale" OR "pinniped" OR "sirenian" OR "sea turtle" OR ("diving" w/10 "seabird") OR "shark" OR "ray" OR "skate" OR "fish" OR ("mobile" w/10 "invertebrate") OR "sessile invertebrate")

2.2. Experts' workshop

Once a first draft of the definition and mechanisms of displacement was compiled, an online workshop was organized with 16 scientists from six countries. The participants were invited based on their expertise in effects of ocean renewable energies (i.e., mainly marine energy and offshore wind) on marine mammals, fish, seabirds, and invertebrates, and their expertise with the various methods of investigation used in the field. During the workshop, participants provided feedback and edits to a working document (unpublished) to refine the definition of displacement and discussed several topics: the division of species into functional groups and the characteristics of each group; the spatiotemporal scales relevant to each functional group; the data needs and limitations for investigating displacement; what information is needed for marine energy projects to reduce the risk of displacement; and what lessons from other industries (both marine- and land-based) can be transferred to marine energy.

Comments provided by the workshop participants were leveraged to improve the definition, synthesize information about the functional groups, describe numerical models and methods of field data collection, and identify remaining knowledge gaps. Overall conclusions from the workshop were that 1) now is the time to start thinking about animal displacement from marine energy development because arrays of devices are being planned and there is a better understanding of the main stressor-receptor interactions of concern (Copping et al., 2020), although questions remain about how they would scale up (Hasselman et al., 2023); 2) functional groups are the key to understanding the consequences of displacement and the cascading effects through the ecosystem; and 3) many knowledge gaps remain that need to be addressed in parallel to progressing the marine energy industry.

The remaining sections below describe the proposed definition of displacement, how the various functional groups may be affected, proven methods of investigation, and outstanding knowledge gaps.

3. Displacement: definitions and process

Definitions of displacement that are relevant to marine energy development can be found in a limited number of recent references but are not consistent, nor do the authors agree on which organisms to consider, and/or the processes and consequences of displacement. These earlier definitions are listed first, then we provide our own understanding of displacement.

3.1. Definitions of displacement from the scientific literature

Displacement has only been defined by a few studies in the context of marine energy, mainly related to marine mammals or fish. For example, Long (2017) defined displacement as the "potential for the loss of habitat due to disturbance or barrier effects. This may be in the form of redistribution from an area or complete avoidance of an area".

Sparling et al. (2020) defined displacement as "the movement of animals away from the area within or immediately adjacent to an area in which an anthropogenic activity is occurring or has occurred". The authors highlighted that displacement may be the result of habitat loss (i.e., "the habitat held for the animal is no longer present. Therefore, animals must go elsewhere for a resource that they previously found there") or of disturbance (i.e., "the anthropogenic activity creates a response in an animal that results in a behavioral change").

Copping et al. (2021) defined displacement as the result of a partial or complete loss of preferred or essential habitat or because "an array of marine energy devices placed in a line or large installation might cause a disturbance that acts as a barrier, causing resident fish to move away from the area and/or migratory fish to modify their routes". Moreover, the authors added that "displacement of fish from their preferred habitats is likely to occur across much greater spatial and temporal scales than the avoidance behavior of individual fish or schools of fish when faced with an instream tidal or river turbine".

Buenau et al. (2022) argued that "marine energy arrays may displace animals, fully or partially, from foraging or breeding habitats, if the arrays are located in those areas or are perceived as barriers to access. Displacement could also lengthen migration routes, thereby increasing energetic costs and changing access to prey; all of these factors could lead to population-level effects. Under this definition, displacement is caused by the presence of an array of devices as distinguished from related noise, electromagnetic fields, or other stressors".

Displacement is also an interaction used by the wind industry (land-based and offshore) mainly in relation to birds and bats. Marques et al. (2021) contrasted displacement and attraction based on habitat availability: "We consider displacement as the reduced density of birds occurring near wind turbines, due to long-term disturbance leading to functional habitat loss [...]. Conversely, we define attraction as an increase in bird density within or near the wind farm." Similarly, SEER (2022) distinguished displacement from avoidance and a barrier effect, defining displacement as "limiting the normal use of an area within or adjacent to a wind farm, such as resting, roosting, or foraging habitat"; avoidance as "an action taken by a bird to prevent interaction with the infrastructure of a wind farm"; and a barrier effect as the alteration of a bird's flight behavior that "prevents it from accessing an area".

All these studies described displacement as some combination of habitat loss, a response action, and a barrier to access, more often due to the physical presence of marine energy devices or wind turbines. However, displacement may be a more complex interaction, involving multiple stressors, as described in the following section.

3.2. Proposed definition for displacement for marine energy

Displacement is "the moving of something from its place or position" (Oxford Dictionary). In the marine energy context, we propose to define displacement as the outcome of one of three mechanisms (i.e., attraction, avoidance, and exclusion) triggered by a receptor's response to one or more stressors acting as a disturbance, with various consequences ranging from individual to population level effects (Fig. 1).

A number of stressors are most likely to trigger a response from marine animals, including the physical presence of marine energy devices in their natural environment, the movements of (parts of) devices including the rotation of turbine blades, the underwater noise or electromagnetic fields emitted by the devices and/or associated equipment. In addition, changes in habitats including the creation of artificial reefs and hydrodynamic changes due to the operation of large numbers of devices may also elicit a response from animals. The response, however, will depend on the sensory capabilities and behavior of particular species or individuals, the various combinations and/or cumulative effects of these stressors, and the characteristics of a marine energy project (e.g., technology type, area occupied, duration).

Responses to these stressors may include attraction, avoidance, or exclusion (Fig. 2), or an animal may have no response to the stressor at all. These responses are expected to be species-specific and may vary across different life stages and/or populations, as well as location-specific to some extent, perhaps driven by physical factors such as seascape, depth, hydrodynamics, or the presence of other anthropogenic activities. The ability (or decision) to respond may also vary through time, based on the behavior of an animal or the swim mechanics. Attraction can be defined as the movement of animals towards an area within or immediately adjacent to a marine energy array (i.e., going towards); avoidance is the intentional bypassing of an area with marine energy devices in order to go in the same general direction (i.e., going around); and exclusion is the departure or movement away from the area, so the animal is no longer going towards the initial direction (i.e., going away from). Exclusion can result in a barrier effect, preventing animals from passing through an array of marine energy devices and/or associated equipment. These mechanisms can apply to migratory species along their travel route (e.g., grey whales migrating between Mexico

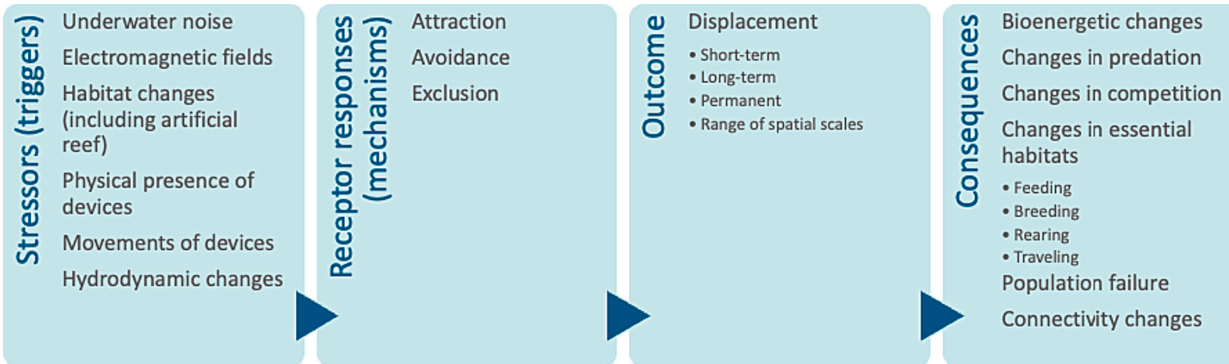

Fig. 1. Displacement flow chart: displacement is the outcome of one of three mechanisms triggered by a receptor's response to stressors, with the potential for a range of consequences on marine animals that span from effects on the individual to effects on populations.

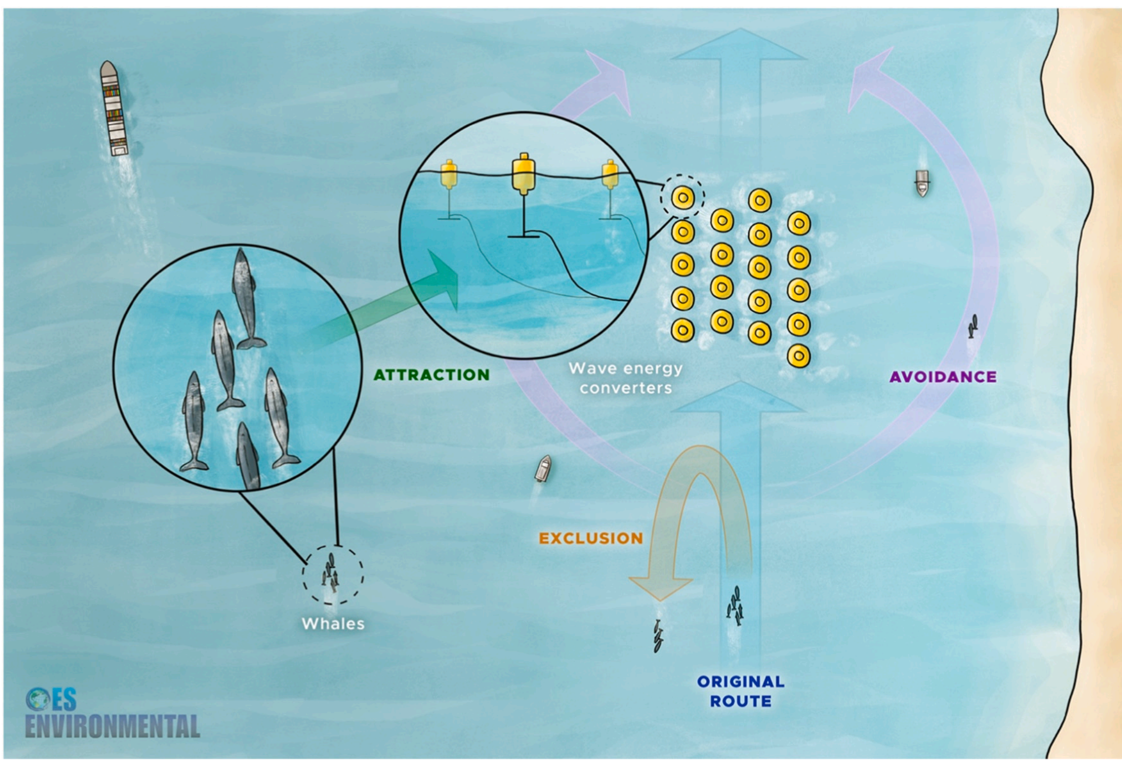

Fig. 2. Mechanisms of displacement: upon encounter with an array of marine energy converters, animals may exhibit no response, or exhibit an attraction, avoidance, or exclusion response that may result in their displacement from key foraging or breeding grounds.
(Illustration by Stephanie King, Pacific Northwest National Laboratory).

and Alaska in the Pacific Ocean), as well as to mobile resident animals that move within small home ranges (e.g., rockfish navigating between rocky reefs) or sessile animals that disperse through pelagic larvae able to react to various cues (e.g., oyster larvae that swim along gradients of sound; Williams et al., 2022).

As an outcome of these receptor responses, displacement can be short-term, long-term, or permanent. A short-term displacement may occur during the installation of devices, resulting in affected animals returning to using the area once construction activities are completed. Short-term displacement may also occur if animals are sometimes disrupted from their day-to-day activities around a marine energy array. Some animals may take more time to adjust to a new baseline but may resume their activities in the marine energy development area, which can be considered a long-term displacement. Permanent displacement may occur if animals never return to an area. On a spatial scale, the outcome of displacement can occur at a range of scales, depending on the migratory or home range of the animals or physical and oceanographic attributes of particular sites.

Displacement of animals is likely to result in a diversity of consequences from the individual to the population level. A displaced animal may experience bioenergetic losses due to the extra time and effort spent travelling around (avoidance), towards (attraction), or away from (exclusion) a marine energy array, if animals are not able to compensate by exploiting additional food sources. In contrast, attraction may result in bioenergetic benefits for individuals upon arrival with new food resources available. If experiencing increased predation risk and/or competition, or increased risk of harm or injury from human activities, when forced into the new areas, the fitness and population survival of the displaced animals will be impacted. Displacement may also lead to the loss of essential habitats that sustain vital functions such as feeding, breeding, spawning, rearing young, or provide a corridor between critical habitats. When multiple individuals within a population are affected, at a sufficiently severe level, displacement could result in failure of the whole population. Displacement may become a further stressor on populations of endangered species already at risk due to an accumulation of stressors to date, such as the southern resident killer whales in the Puget Sound (northwest United States) and adjacent waters that are exposed to water pollution, vessel traffic, and low prey availability (NOAA Fisheries, 2023). In contrast, animals displaced by attraction may thrive in their new environment, gaining new essential habitat and increasing their population, such as predators attracted to artificial reefs and the prey that they concentrate; this can also lead to other benefits such as spillover effects. However, it is important to recognize that such attraction could also lead to negative effects in the areas prey and predators are displaced from (Langhamer, 2012; Broadhurst et al., 2014; Sheehan et al., 2020).

In summary, in the context of response to the presence and/or operation of marine energy devices, displacement of aquatic animals is defined as the result of mechanisms that cause animals to depart from or not enter their preferred or critical habitats, or to move into the newly provided habitats.

4. Organisms of concern and scale of effect

Many marine animals may be susceptible to some level of displacement once large marine energy arrays are increasingly integrated into the seascape, including large migratory animals (e.g., whales, sharks), non-migratory pelagic animals with large home ranges (e.g., smaller cetaceans, large pelagic fish), and benthic and demersal mobile organisms with more limited ranges (e.g., bottom fish, crustaceans), among many others.

4.1. Delineation of functional groups

Mechanisms and outcomes of displacement may be species-, site-, or life stage-specific. However, for the purpose of this study it was useful to place the marine animals within functional groups (Table 2). Because there is a lack of empirical data on many marine species, it is impossible in a predictive sense to work on a species-specific basis, and a functional group approach assists with the generalization of findings from one site or study to another. The groups are based on specific characteristics that animals have in common, including their tendency to:

- be migratory (i.e., travel seasonally between habitats for feeding and reproduction purpose), transient (i.e., exhibit unstable spatiotemporal use of habitats), or resident (i.e., live year-round in the same area);
- inhabit the pelagic (i.e., water column) or benthic/demersal (i.e., close to the seafloor) realms; and
- live in groups or as single individuals.

Animals' behavioral responses to the presence of marine energy arrays may depend on these factors and others, such as their maneuverability (i.e., ability to move easily in the presence of obstacles) and swimming ability (mostly horizontal, vertical, or in all dimensions). While there remains a lot to learn about each species and functional group, a detailed list of knowledge gaps for each of them is not the goal of this review, but instead to provide an overview of how we can expect displacement to affect them with marine energy arrays in place.

4.2. Overview of the functional groups

The types of stressors, responses, and consequences of displacement for each of these groups of animals remain hypothetical until detailed field observations can be made to confirm that drawing generalities based on these shared characteristics is valid (Fig. 3). While most consequences and outcomes for marine animals associated with marine energy arrays are expected to be neutral, or negative like bioenergetic and/or habitat loss, there is also the possibility that some positive outcomes could occur (Fig. 1). For example, an array might provide new suitable habitat for some animals, allowing them to better pursue their prey, colonize safe rearing habitat, and perhaps avoid fisheries interactions. Although research on displacement of marine animals around wave and tidal devices remains limited, some insight can be drawn from studies around other marine industries, especially offshore wind.

4.2.1. Large whales and large sharks

There is limited research on marine energy impacts on large, and relatively slow moving, species of whales or sharks. Large whales could be displaced during installation and operation activities due to underwater noise generated by piling and additional vessel traffic, which may lead to potential exclusion from foraging areas or to a disturbance in communication needed during feeding (Kraus et al., 2019). Large whales may also respond to the physical presence of marine energy

Table 2
Functional groups of animals most susceptible to some level of displacement from a marine energy array.

Functional group	Movement	Location	Group size	Notes
Large whales & large sharks	Migratory	Pelagic	Groups; Individuals	Limited maneuverability around devices, seasonal migrations, echolocate (whales)
Small cetaceans	Transient; Resident	Pelagic	Groups; Individuals	Very maneuverable, swim in 3D through areas with obstacles, splitting a group if needed, echolocate, may forage benthically
Pinnipeds	Migratory; Resident	Pelagic	Groups; Individuals	Very maneuverable, swim in 3D through areas with obstacles, splitting a group if needed, do not echolocate, may forage benthically
Sirenians	Resident	Benthic	Groups; Individuals	Less maneuverability, mainly swim on bottom, nearshore, do not echolocate
Sea turtles	Migratory	Pelagic	Individuals	Very maneuverable but slow, swim in 3D through areas with obstacles, seasonal migrations
Diving seabirds	Migratory; Resident	Pelagic	Groups; Individuals	Will enter the ocean from above, very maneuverable
Pelagic sharks, fish & invertebrates	Migratory; Transient	Pelagic	Groups; Individuals	Very maneuverable, swim in 3D through areas with obstacles, some migrate, some engage in diel vertical migrations
Forage fish	Migratory; Transient	Pelagic	Groups	Swim in 3D as a group around obstacles, splitting a group if needed, some migrate, some engage in diel vertical migrations
Benthic sharks, skates, & rays	Resident	Benthic	Individuals	Mainly swim on bottom
Demersal fish	Migratory; Resident	Benthic	Group; Individuals	Mainly swim on bottom, some migrate, some disperse through pelagic larvae
Mobile benthic invertebrates	Migratory; Resident	Benthic	Individuals	Mainly crawl on bottom, some migrate, some disperse through pelagic larvae
Sessile invertebrates	Resident	Benthic	Group; Individuals	Disperse through pelagic larvae

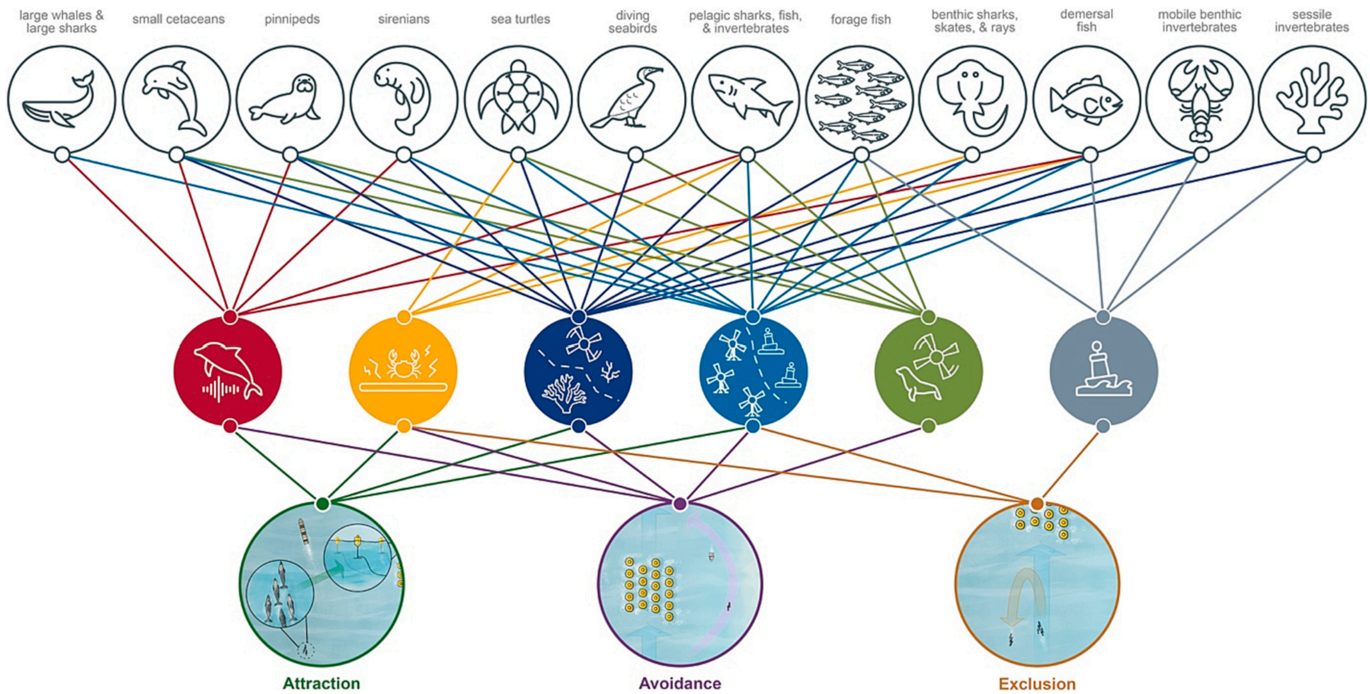

Fig. 3. Potential triggers and responses for each of the animal groups identified in Table 1. Each of the three mechanisms for displacement (left to right: attraction, avoidance, and exclusion) are shown in the bottom row, with unique colored arrow representing each mechanism. Each mechanism connects to the six triggers, also called stressors, in the middle row (left to right: underwater noise, electromagnetic fields, habitat changes, physical presence of devices, movement of devices, and hydrodynamic changes). Each of these stressors connect to the range of marine animals that may be affected, in the top row.
(Illustration by Stephanie King, Pacific Northwest National Laboratory).

arrays by avoiding the area. For instance, grey whales that feed on infauna and epifauna in soft bottom habitats could be displaced by the presence of device foundations and cables at marine energy sites (Horwath et al., 2021). The outcome from these disturbances may be a permanent displacement unless the whales become habituated over time.

Basking sharks enter offshore wind sites but the risk of displacement has been determined to be low because of their low habitat selectivity and limited responses to increased vessel traffic (Booth et al., 2013). There may still be some risk of displacement however, as basking sharks are opportunistic feeders, and forage in areas with high prey densities; if marine energy devices alter distributions of prey, displacement of basking sharks may occur.

The potential consequences of displacement of large whales and sharks may include some bioenergetic loss due to loss of feeding habitat and longer travel routes, and/or delays in reaching breeding or feeding habitat.

4.2.2. *Small cetaceans*

Small cetaceans' improved swimming and maneuvering capabilities put them less at risk of displacement compared to larger cetaceans. However, marine energy deployments may displace small cetaceans because of noise generated by the devices and/or during construction activities, or increased vessel traffic during construction and maintenance activities, which have been shown to cause behavioral responses in harbor porpoises and bottlenose dolphins (Dähne et al., 2014; Graham et al., 2017; Brandt et al., 2018). Harbor porpoises especially might be displaced by the turbines' underwater noise acting as deterrent (Lossent et al., 2018; Pine et al., 2019). Lower detection rates of harbor porpoises were observed at decreasing distance from the turbines of a small array, and reduced abundance as turbines became operational indicated localized avoidance behavior (Gillespie et al., 2021; Palmer et al., 2021). However, harbor porpoises appear to become habituated to disturbance over time and are only temporarily displaced (Thompson et al., 2013; Robertson et al., 2018). Impacts on harbor porpoises and other small cetaceans resulting from displacement are most likely site-specific, and local activity has been shown to resume shortly after construction or maintenance disturbance (Tollit et al., 2019).

4.2.3. *Pinnipeds*

Harbor seals have exhibited small scale redistributions, reduced abundances, and avoidance behavior from 200 m up to about 2 km from operating tidal turbines (Savidge et al., 2014; Hastie et al., 2017; Sparling et al., 2017; Joy et al., 2018; Onoufriou et al., 2021). Seals decreased transits by 20 % through a tidal energy site when devices were operational, and exhibited decreased abundances during installation and operation, indicating avoidance and habitat loss due to disturbance (Savidge et al., 2014; Sparling et al., 2017; Joy et al., 2018). Harbor seals may exhibit altered behavior up to 100 m away from a tidal turbine due to underwater noise (Robertson et al., 2018). However, seals were not observed avoiding areas during the installation and operation of wave energy devices (Sparling et al., 2020). Risking disturbance from device-associated underwater noise may outweigh the benefits of foraging for seals, particularly in low prey density areas (Hastie et al., 2021). Lessons learned from offshore wind farms showed that pile driving noise can cause temporary displacement of harbor seals with recovery occurring within 2 h after the cessation of piling (Russell et al., 2016) but this construction method is rarely employed for installing marine energy devices, although the less noisy pin pilling method has sometimes been used (Morandeau et al., 2013).

4.2.4. *Sirenians*

Both manatees and dugongs have been observed altering their behavior in response to boat traffic within 50 m. This can cause a reduction or cessation of feeding and relocation to areas without boats (Nowacek et al., 2004; Hodgson and Marsh, 2007). The increase in boat traffic for construction and maintenance activities at marine energy sites could potentially displace sensitive sirenians, especially in shallow feeding areas. However, there is very limited research about the risks and impacts of marine energy devices on sirenians as the waters these animals inhabit are seldom appropriate for marine energy projects development.

4.2.5. Sea turtles

Research on sea turtle response to marine energy devices is very limited. However, like other motile species, temporary displacement due to underwater noise is likely to occur during construction activities but is not expected to have long-term consequences, while habitat loss may occur without careful siting (BOEM, 2021). Various efforts are being made to monitor and track sea turtle movement, distributions, and abundances in order to better understand the impact that renewable energy development could have on their populations (Gitschlag et al., 2020).

4.2.6. Diving seabirds

Most of the research on displacement of seabirds has been conducted around offshore wind farms, with research on tidal and wave device effects on diving seabirds associated with collision risk rather than displacement. Displacement was found consistently to be site- and species-specific. In the United Kingdom, species considered at risk of displacement from wind turbines include black guillemots, eider ducks, razorbills, Atlantic puffins, terns, northern gannets, and great cormorants (Willmott et al., 2013; Rehfisch et al., 2014). Seabirds that are likely to be vulnerable to displacement include sea ducks, alcids, loons, divers, auks, gannets, and grebes due to high avoidance rates at large scales (Willmott et al., 2013; Krijgsveld, 2014; McGovern et al., 2016; Kelsey et al., 2018). Seabird species that are likely to show low displacement vulnerability are gulls and jaegers/skuas; however, they are at greater risk of collision due to low avoidance behavior (Bradbury et al., 2014; Kelsey et al., 2018). Site-specific displacement could be due to factors such as decreases in habitat quality or food availability, or attraction to the presence of certain device features such as lighting or roosting habitat provided by above-water structures (Dierschke et al., 2016) or the enhancement of oceanographic features such as kolk boils (Slingsby et al., 2022). Factors that can put seabirds at higher risk of displacement are endemism to a specific area, threat status, and population vulnerability (Adams et al., 2016; Kelsey et al., 2018).

4.2.7. Pelagic sharks, fish, and invertebrates

Pelagic sharks and large fish such as sturgeon and salmon occasionally come into close proximity with subsea cables at marine energy sites, causing some concern for potential displacement in the form of attraction or avoidance behaviors due to electromagnetic fields (EMFs) (Gill et al., 2012; Wyman et al., 2018). However, these effects are likely to be minimal, causing little to no response (Snyder et al., 2019). In addition, underwater noise generated by operating devices may attract or deter pelagic fish (Leis et al., 2011; Copping et al., 2021), as well as some pelagic invertebrates such as squid (Jones et al., 2021), but long-term consequences of such displacement remain unknown.

4.2.8. Forage fish

Avoidance by fish schools near tidal turbines has been observed around operating turbines, which could be due to noise, visual stimuli, or changes in flow patterns (Fraser et al., 2018; Grippo et al., 2020). Reduced fish presence could also be due to increased construction and maintenance activities and increased vessel traffic (Staines et al., 2019). Pelagic forage fish such as the horse mackerel feed mostly on pelagic food items, rather than biofouling growth on artificial structures, indicating that if they are attracted to offshore structures it may be for reasons other than foraging opportunities (Mavraki et al., 2021). However, at some sites, attraction of fish schools was seen with increased fish densities near various marine energy and offshore wind structures, which could be due to the artificial reef effect and increased food sources or shelter options (Fraser et al., 2018; Williamson et al., 2019). Whether artificial reefs are attracting animals away from natural habitats or enhancing local production is a long-debated topic (Pickering and Whitmarsh, 1997) and out of scope of this study. Forage fish displacement response to marine energy devices is most likely site- and species-specific, based on differing habitat characteristics and feeding opportunities.

4.2.9. Benthic sharks, skates, and rays

Some species of benthic sharks, skates, and rays may be attracted to the EMF emitted by marine energy devices or cables, an abundance of prey within the array, and/or the physical presence of the devices to which they can attach their egg cases; they may also avoid a marine energy area due to seabed disturbance. This displacement could be short-term to permanent, depending on the suitability of the new habitat. However, research is limited and studies have observed negligible effects, indicating significative avoidance or attraction behavior is unlikely (Snyder et al., 2019; Maxwell et al., 2022).

4.2.10. Demersal fish

Demersal fish may be attracted to new habitats created by the presence of marine energy devices, for shelter, food, and other attributes. Effects on demersal fish may be species-specific, as a study on the viviparous eelpout found no effect, positive or negative, of offshore wind turbine foundations on body condition or reproductive health, and observed no attraction or avoidance effects; however, attraction to the structures was observed for other species like cod, eel, and sculpin (Langhamer et al., 2018). Benthic species like cod, pouting, and sculpin may be attracted to offshore structures to feed on the artificial reef habitat, as shown by the presence of fouling organisms in stomach contents (Mavraki et al., 2021). However, attraction to marine energy structures is likely to be site-specific, as cod and pouting were differently attracted at different offshore wind farms (Reubens et al., 2013). Fish larvae, too, may be attracted to the marine energy arrays, especially once biofouled, if the acoustic and chemical cues resemble those of natural reefs (Anderson et al., 2021; Cresci et al., 2023). Marine energy structures installed on the seabed can also alter the hydrodynamics of an area (Whiting et al., 2023), potentially affecting larval dispersal of demersal fish. This may result in some larvae being displaced to potentially less suitable habitats (van Berkel et al., 2020; Horwath et al., 2021). The resuspension of sediments around operating marine energy devices and during construction activities may also temporally displace benthic and demersal fish, although spatiotemporal scales of such disturbance are relatively small (Taormina et al., 2018).

4.2.11. Mobile benthic invertebrates

Research on displacement of mobile benthic invertebrates, such as decapods or octopuses, has been limited to attraction to the devices as artificial reefs, and the attraction or repulsion effects of EMFs. Marine energy sites that act as artificial reefs may attract invertebrate assemblages new to the area as novel habitats are created, providing shelter and food sources (Langhamer, 2016; Todd et al., 2018), most likely attracted as larvae by acoustic cues (Montgomery et al., 2006; Anderson et al., 2021). However, while the attraction of mobile invertebrates to these new habitats can be beneficial by increasing local biodiversity, keeping in check biofouling growth, and providing food sources for higher trophic levels, it may also increase the risk of heightened exposure to EMFs or underwater noise generated by the marine energy devices and cables for these mobile invertebrates (Lossent et al., 2018; Gill and Desender, 2020). Although there is no evidence that adult decapods may be attracted or repulsed by the level of EMFs emitted by marine energy cables, there may be physiological effects on larvae and juveniles (Gill and Desender, 2020).

4.2.12. Sessile invertebrates

Any submerged structures of deployed marine energy devices and offshore wind turbines (e.g., foundations, moorings), as well as the surrounding sediments, are rapidly colonized by biofouling organisms and sessile invertebrates (Degraer et al., 2021; Want et al., 2017). In addition to attracting mobile animals, the new hard substrate created by marine energy devices can provide habitat for settling of pelagic larvae of sessile invertebrates and lead to heavily colonized artificial reefs. Larvae may settle on these novel artificial structures before reaching nearby natural habitats, especially if attracted by the soundscape or other cues around marine energy devices (Lillis et al., 2015; Morello and Yund, 2016; Williams et al., 2022). The novel artificial habitats may also create a stepping-stone effect, causing populations to occupy areas not originally accessible (Adams et al., 2014). While generally a positive impact, this increased connectivity between natural and artificial habitats facilitated by the dispersal of planktonic larvae could benefit invasive species, causing space competition and habitat loss for native invertebrate species (Adams et al., 2014; Dannheim et al., 2020; Horwath et al., 2021).

5. Methods of investigation

Both numerical models and field-based approaches are necessary to fully investigate how displacement may affect various groups of marine animals and assess the role this interaction may play in their survival. Importantly, well-designed pre-installation (i.e., baseline) and post-installation data collection campaigns and modeling studies will help address remaining knowledge gaps. However, meaningful field observations will not be possible until arrays of wave or tidal devices are deployed and operational.

5.1. Numerical models or frameworks relevant to displacement

A number of studies have already highlighted the use of numerical models or analytical frameworks to assess the potential impacts of marine energy devices (Buenau et al., 2022; Sparling et al., 2020). Until arrays of wave or tidal devices are deployed, these models or frameworks can help estimate the movements of individual animals around arrays (e.g., agent-based models), suitable habitat for a species or population (e.g., species distribution models), changes in animal distribution in a development area (e.g., generalized linear mixed models or generalized additive models), and the population and/or bioenergetic consequences of displacement (e.g., population consequences of disturbance framework, population dynamic models, or dynamic energy budget models).

Agent-based models, also called biophysical models, have been used to represent the movement of harbor porpoise and fish around tidal turbines (Grippo et al., 2020; Lake et al., 2015), producing simulated trajectories of each individual and a predicted spatial distribution for the population, which can be used for assessing changes over time. Often employed to assess the potential results from animal collisions with tidal turbines, these models could be applicable to simulating the mechanisms of animal displacement from marine energy sites.

Species distribution models, also known as habitat suitability models, are well used in marine ecology and have been employed in a few studies to simulate changes in the probability of occurrence of species before and after deployment of marine energy devices, especially to assess potential displacement of target species due to large-scale marine energy projects (Baker et al., 2020; du Feu et al., 2019). Somewhat similar in their goal to species distribution models, statistical models (e.g., generalized linear mixed models or generalized additive models) have been used to assess the associations between seabird distribution and oceanographic and physical features in areas suitable to tidal energy development (Waggitt et al., 2016), as well as to model the changes in seasonal distribution of harbor porpoises in relation to anthropogenic activities (Gilles et al., 2016).

Several models exist to assess the population consequences of a disturbance that can be applied to displacement. Applications of the interim population consequences of disturbance (iPCoD) framework initially focused on potential impacts of underwater noise and collision on marine mammals and can be applied to animal displacement (King et al., 2015; Sparling et al., 2020). However, in the absence of suitable field data, the iPCoD model relies on expert elicitation to quantify how behavior changes in response to exposure to pile driving noise would translate in changes in energetic state and ultimately vital rates. Population viability analysis (PVA) is another approach used to model the population consequences of disturbances. PVA was developed to assess population extinction risks due to anthropogenic activities and could be applied to the context of displacement around marine energy sites, with caveats similar to those of the iPCoD approach in that there is a lack of empirical data to inform how predicted behavioral effects will translate into effects on vital rates (Sparling et al., 2020).

Based on the dynamic energy budget (DEB) theory (Kooijman, 2010), DEB models infer the allocation of bioenergetic resources for maintenance, growth, and reproduction, and can be used to predict the energetic consequences resulting from a disturbance (e.g., displacement) for individuals. Coupled with a population model like those described above, DEB models can also predict consequences for populations. A DEB model was recently developed for several marine mammal species for assessing marine energy and offshore wind consequences in the United Kingdom, and work is underway to incorporate into the iPCoD framework (Harwood et al., 2020).

These numerical models and analytical frameworks can provide an assessment of consequences of displacement on marine populations' health and distribution, which can be especially useful for impact assessment of a new marine energy project. However, there remains a mismatch between the resolution of field-collected data, model needs, and the actual density and distribution of populations of marine species of concern.

5.2. Field data collection

Numerical models and analytical frameworks need input data for parameterization and validation, especially robust three-dimensional assessments of habitat use for the species and/or populations of concern, including timing and routes of migrations for migratory species. Some of these data are available from natural resource management agencies and wildlife researchers and should be examined before any additional data collection is proposed.

Assuming that additional field data are needed, baseline field observations should be collected before the installation of arrays. In addition, post-installation monitoring data are needed to assess the outcomes and validate models. A variety of methods that do not interfere with animal behavior can be employed to collect baseline and post-installation data (Fig. 4; Isaksson et al., 2020), using the same methods to ensure meaningful comparisons:

- Land- and boat-based surveys to record surface presence and habitat use of animals like marine mammals, pelagic sharks, sea turtles, and diving seabirds (Lieber et al., 2019; Williamson et al., 2018).
- Passive acoustic underwater monitoring with hydrophones for vocalizing animals like cetaceans and some fish species (Porskamp et al., 2015; Tollit et al., 2013).
- Active acoustic monitoring with echosounders, mainly for fish (Staines et al., 2019; Williamson et al., 2021).
- Telemetry to track three-dimensional movements of marine animals (e.g., marine mammals, sea turtles, sharks, and fish), using either acoustic or satellite tags that record at least location and depth at regular intervals (Hastie et al., 2016; Sanderson et al., 2023).
- Underwater imagery/video surveys to record underwater presence and habitat use, particularly valuable for slow-moving animals (Broadhurst et al., 2014; Hemery et al., 2022).
- Aerial surveillance with drones for animals with occasional presence at the sea surface, as long as cloud cover and inclement weather do

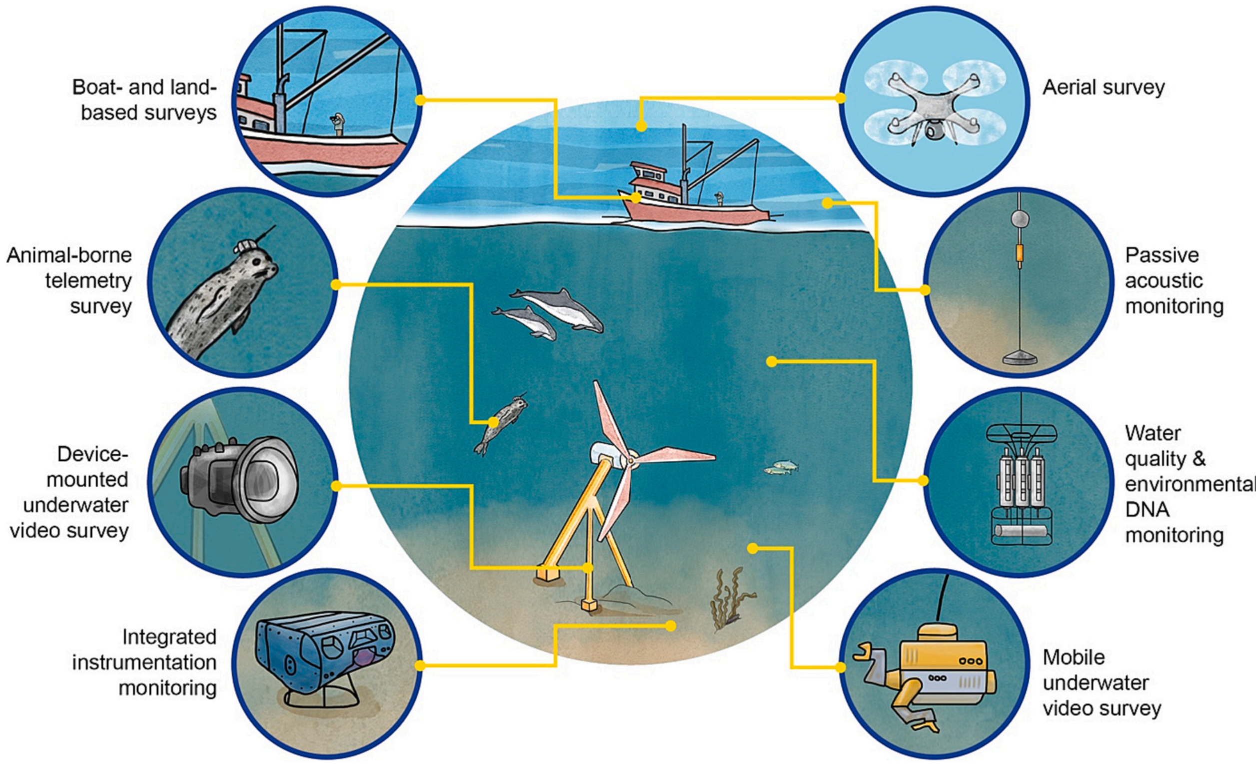

Fig. 4. Graphical representation of commonly used survey methods available to assess animal use of marine energy environments and interactions with marine energy devices. Clockwise from top right: aerial survey with drones or aircrafts; passive acoustic monitoring with hydrophones; water quality and environmental DNA monitoring with rosettes of samplers; mobile underwater video survey with remotely operated vehicles; integrated instrumentation monitoring with platforms combining multiple sensors; device-mounted underwater video survey with cameras attached to devices; telemetry survey with biologgers or acoustic tags attached on or implanted in animals; and boat- and land-based vantage point surveys with human observers.
(Illustration by Stephanie King, Pacific Northwest National Laboratory; inspired from Isaksson et al., 2020).

not affect the technology (Lieber et al., 2019; Williamson et al., 2018; Slingsby et al., 2022).
- Environmental DNA to record presence and habitat use of specific species or groups of species from water samples only (Dahlgren et al., 2023), perhaps more successful when combined with underwater imagery (Mirimin et al., 2021; Kopp et al., 2023).

These methods have all been proven efficient and cost-effective for collecting useful information on animals' presence, behavior, and habitat use around single wave or tidal energy devices (Hasselman et al., 2020), as well as in other contexts such as monitoring around offshore wind or oil and gas installations. These types of observations and data collection methods have pertinence broadly to interactions of the marine animals of interest for displacement.

6. Remaining knowledge gaps

There is still little known about the mechanisms and significance of animal displacement around marine energy sites to fully understand, and when necessary, mitigate, these interactions. Remaining knowledge gaps include information on the distribution and behavior of the marine animals of concern, on potential effects of the marine energy technologies, and how the animals and the technologies interact. In addition, there are no suitable regulations for ensuring that displacement does not harm marine species.

Gaps specific to marine animal displacement include:

- Which species that are most likely to be affected by displacement;
- How those species behave and how they use their habitats;
- What the triggers, mechanisms, and consequences of displacement are for each species, or at least functional groups;
- How behaviors and biological rates differ among life stages, individuals, or populations within a species;
- What spatiotemporal scales of displacement are relevant to each species and life stage;
- How consequences of displacement of individuals translate to the population or species levels; and
- How to understand displacement in the context of climate change and other cumulative effects.

Gaps specific to marine energy technologies include:

- Which array configurations (e.g., size, geometry, spatial coverage, cable route) and/or device types are most likely to cause displacement and in which type of environment;
- How underwater noise and/or EMF emissions scale up with arrays (Hasselman et al., 2023); and
- Which surrogate marine and/or terrestrial activities may inform this interaction.

Gaps specific to monitoring displacement include:

- Which commercial-off-the-shelf monitoring technologies are most suitable for each species and how to adapt them to different sites and marine energy technologies;
- Whether existing observation technologies can be modified or new technologies need to be developed;
- What spatiotemporal scales should the monitoring surveys cover for each species and marine energy technology; and
- How to monitor displacement in the context of climate change and other cumulative effects.

Gaps specific to the regulatory context include:

- Which existing specific national or international regulations or statutes apply to displacement of marine animals (related to marine energy and/or other sectors);
- Under which common regulations that already protect species and populations could these interactions fall into; and
- Whether any actions regarding displacement are required by law or recommended.

Investigating any or all of these questions will greatly enhance our understanding of displacement around marine energy arrays and its consequences for marine animals.

7. Conclusion

To move forward with investigating and understanding the risk of displacement for marine animals around marine energy arrays, the marine energy community must first agree on the definitions, mechanisms, and consequences of displacement. Leveraging definitions laid out in previous marine energy studies and those related to offshore wind, as well as discussions with subject matter experts, we have defined displacement as the outcome of one of three mechanisms (i.e., attraction, avoidance, and exclusion) triggered by a receptor's response to one or more stressors acting as disturbance, with various consequences at the individual through population levels. Although this stressor-receptor interaction is unlikely to be a concern until the marine energy industry deploys large arrays, it is important to 1) agree on the definition of displacement, 2) understand the potential mechanisms that cause displacement and the possible consequences to marine animals, 3) generate realistic models of such consequences, and 4) identify how to best monitor and mitigate these changes. The knowledge gaps highlighted in this study will help the regulatory and scientific communities prepare themselves for mitigating, observing, measuring, and characterizing displacement of various animals around marine energy arrays in order to prevent irreversible consequences.

CRediT authorship contribution statement

Lenaïg G. Hemery: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Lysel Garavelli:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. **Andrea E. Copping:** Writing – review & editing, Writing – original draft, Resources, Investigation, Funding acquisition, Conceptualization. **Hayley Farr:** Writing – review & editing, Writing – original draft, Investigation. **Kristin Jones:** Writing – review & editing, Writing – original draft. **Nicholas Baker-Horne:** Writing – review & editing, Investigation. **Louise Kregting:** Writing – review & editing, Investigation. **Louise P. McGarry:** Writing – review & editing, Investigation. **Carol Sparling:** Writing – review & editing, Investigation. **Emma Verling:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare no conflict of interest. The project funders had no role in the design of the study, in the synthesis of the available information, in the writing of the manuscript, or in the decision to publish the study.

Data availability

No data was used for the research described in the article.

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