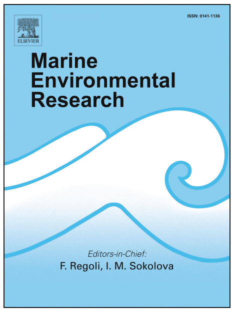

Electric and magnetic senses in marine animals, and potential behavioral effects of electromagnetic surveys

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Electric and magnetic senses in marine animals, and potential behavioral effects of electromagnetic surveys

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Abstract

Electromagnetic surveys generate electromagnetic fields to map petroleum deposits under the seabed with unknown consequences for marine animals. The electric and magnetic fields induced by electromagnetic surveys can be detected by many marine animals, and the generated fields may potentially affect the behavior of perceptive animals. Animals using magnetic cues for migration or local orientation, especially during a restricted time-window, risk being affected by electromagnetic surveys. In electrosensitive animals, anthropogenic electric fields could disrupt a range of behaviors. The lack of studies on effects of the electromagnetic fields induced by electromagnetic surveys on the behavior of magneto- and electrosensitive animals is a reason for concern. Here, we review the use of electric and magnetic fields among marine animals, present data on survey generated and natural electromagnetic fields, and discuss potential effects of electromagnetic surveys on the behavior of marine animals.

KEYWORDS: Magnetism, electrosensitive animals, magneto sensitive animals, electromagnetism, orientation, noise, pollution effects, energy resources, ecosystem management

Commercially deployed since the beginning of the 21th century, electromagnetic techniques (controlled-source electromagnetic sounding, seabed logging, remote reservoir resistivity mapping) have become a common tool in oil exploration. With this technique, electric and magnetic fields are generated to map petroleum deposits under the sea bed (Constable 2006). Many marine animals, however, use electric and/or magnetic fields for orientation and migration, and – as sharks and rays - even for communication, prey detection, and predator avoidance (Collin and Whitehead 2004, Kalmijn 1982, Kullnick 2000). Thus, exposure to electromagnetic surveys may disrupt a wide range of animal behaviors. Between 2009 and 2018, 149 surveys, extending over 4238 days were conducted in Norwegian waters alone (OD 2019). Despite the widespread use of this technique across the globe, studies on its impact on aquatic life are virtually absent from the scientific literature (although potential effects are discussed in industry reports; Buchanan et al. 2006, Buchanan et al. 2011). Here we review the use of electric and magnetic fields among marine animals and discuss potential effects of electromagnetic surveys on the animal's behavior.

1. Electromagnetic surveys

In typical electromagnetic surveys, an electromagnetic source is towed about 30-50 m above the bottom or 10 m under the surface, at a speed of a few meters per second (Buchanan et al. 2006, Buchanan et al. 2011, Key et al. 2012). In another type of system (vertical surveys), the source is placed perpendicular to the sea bottom for an hour, at consecutive stationary positions distributed over the survey area (Ellingsrud and Larsen 2019, Helwig et al 2019). The source produces an alternating electromagnetic field (0.05-10 Hz) which propagates through the water mass and the seabed and is modified by the conductivity of the media it passes through. An array of sensors anchored on the sea bed 0.5 – 3 km apart detect the modified electromagnetic signals and their characteristics are used to model petroleum deposits in the ground (Buchanan et al. 2006, Buchanan et al. 2011, Holten et al. 2009, Johnsson and Oftedal 2011, Key et al 2012). While surveys used to be restricted to deep waters, far from the surface, they are now also taking place over relatively shallow depths. Surface tows are conducted over depths down to 500 m, deep tows are performed at depths down to 3500 m, and vertical stationary surveys in waters from 100 to 1200 m deep. (Buchanan et al. 2011, Ellingsrud and Larsen 2019, Mittet 2016, Mittet and Jensen 2018).

The reported maximum electric and magnetic field strengths are 0.5-6 V/cm and 200 000 nT respectively, but both attenuate rapidly with distance (Fig. 1-2; Ellingsrud 2014, Johnsson and Oftedal 2011, Mittet 2016, Mittet and Jensen 2018). According to Buchanan (2011), the magnetic field is below 200 nT at 400 m distance, and the electric field under 400 nV/cm at 1000-1900 m distance. Mittet and Jensen (2018) report levels at distances in similar order of magnitudes (up to 600 nV/cm and 48 nT at 1000 m distance).

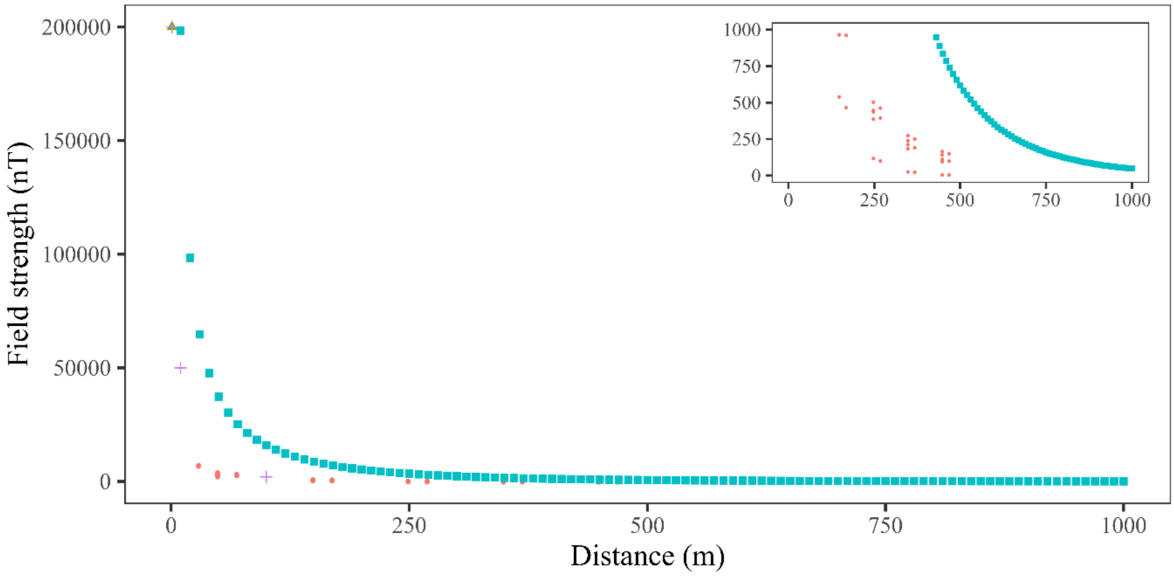

Figure 1. Magnetic field strength by distances from the electromagnetic source. Red points are data from Buchanan (2011) and include deep and shallow towed electromagnetic sources (frequency = 0.1-10 Hz, current = 1 - 1.25 kA) with distances as the vertical distance in line with the towing transect. Purple crosses are data from Johnsson and Oftedal (2011). Blue squares are from modelled data from EMGS for a 1 Hz and 10 kA survey. The inset shows the same figure but with a smaller range on the y-axis (0 – 1000 nT).

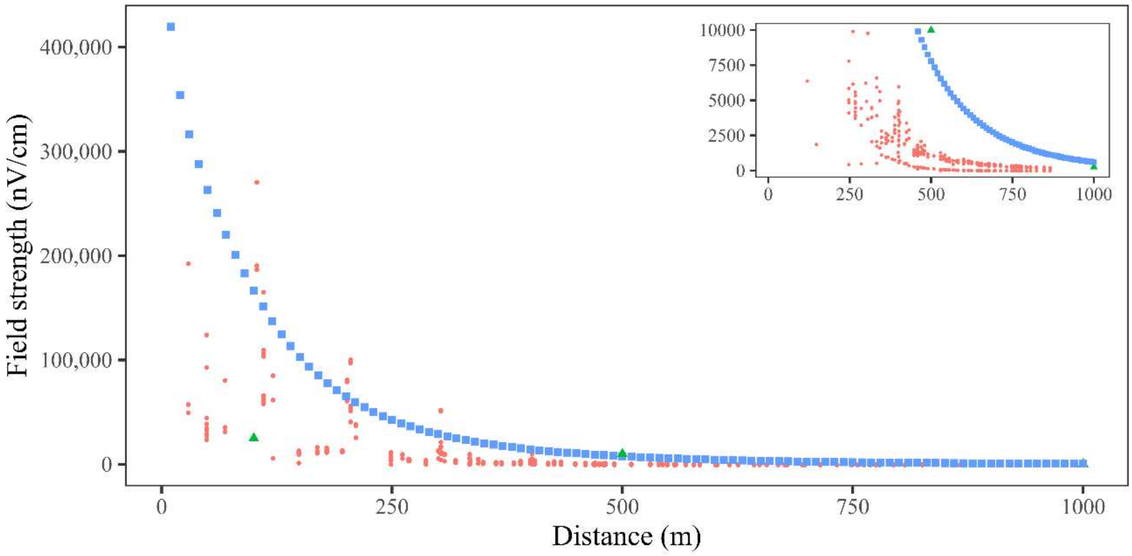

Figure 2. Electric field strengths at different distances from the electromagnetic source. Red points are data from Buchanan (2011) and include deep and shallow towed electromagnetic sources (frequency = 0.1-10 Hz, current = 1 - 1.25 kA) with distances derived from the sum of vertical (up to 750 m) and horizontal (up to 400m) distances from the source. Green triangles are data from Ellingrud (2014). Blue squares are from EMGS for a 1 Hz and 10 kA survey. The inset show the same figure but with a smaller range on the y-axis (0 – 10 000 nV/cm).

2. Electromagnetic fields in nature

In systems in movement, electric and magnetic fields occur together. An electric field is induced in any conductor that is moving through a magnetic field or that is exposed to a changing magnetic field. An electric current in a conductor creates a magnetic field in the space surrounding the conductor (Young and Freedman 1996). Magnetic and electric fields are part of the environment of practically every living organism (Skiles 1985).

2.1 Magnetic fields

The Earth's own magnetic field, the geomagnetic field, is one of the strongest naturally occurring components of the magnetic field that organisms experience. The Earth's magnetic field is produced by currents generated by convection of molten iron in the outer core. It has an inclination and a magnitude (sometimes referred to as intensity) that both vary relatively predictably with geographic location. The inclination is 0° at the magnetic equator and 90° at the magnetic poles while the magnitude is around 60 000 nT at the poles, 40 000 - 50 000 nT at mid latitudes, and 30 000 nT at the equator. This results in an average change of 2-5 nT/km, and 0.01°/km between the equator and the poles. In addition, crystal rocks in the crust and non-dipole components of the core's internal dynamo produce local anomalies, causing magnetic fields several times weaker or stronger than expected, and gradients of 10-100 nT/km (Kullnick 2000, Skiles 1985, Walker et al. 2003). Also, relevant for life on earth, the natural geomagnetic field is constantly changing, and has historically even experienced several pole reversals. Today the total field is changing at a rate of 0 - 120 nT / year depending on geographic location (British Geological Survey 2018, Skiles 1985).

Solar electromagnetic and particle radiation produces solar-terrestrial interactions that cause both small and large magnetic disturbances. Solar-terrestrial interactions cause larger disturbances at higher latitudes, ie. in the auroral zones (the latitudinal bands where northern and southern lights occur most frequently). Local diurnal changes in magnetic field range from a few to over 500 nT (UiT 2018; Klinowska 1986, Skiles 1985). Solar storms, on the other hand, can periodically produce much larger disturbances. The magnitude and frequency of solar storms follow an 11-year solar cycle with quiet and active times. Minor disturbances, occurring in auroral zones, of 100-200 nT typically last 30 min to several hours and occur a few to hundreds of times a year depending on location (Fig. 3-4). Large storms occur more seldom but can cause disturbances of several 1000 nT, and last for days. Both the occurrence of minor disturbances and solar storms vary with the solar cycle. (Brittish Geological Survey 2018, Klinowska 1986; Parkinson 1983; Skiles 1985).

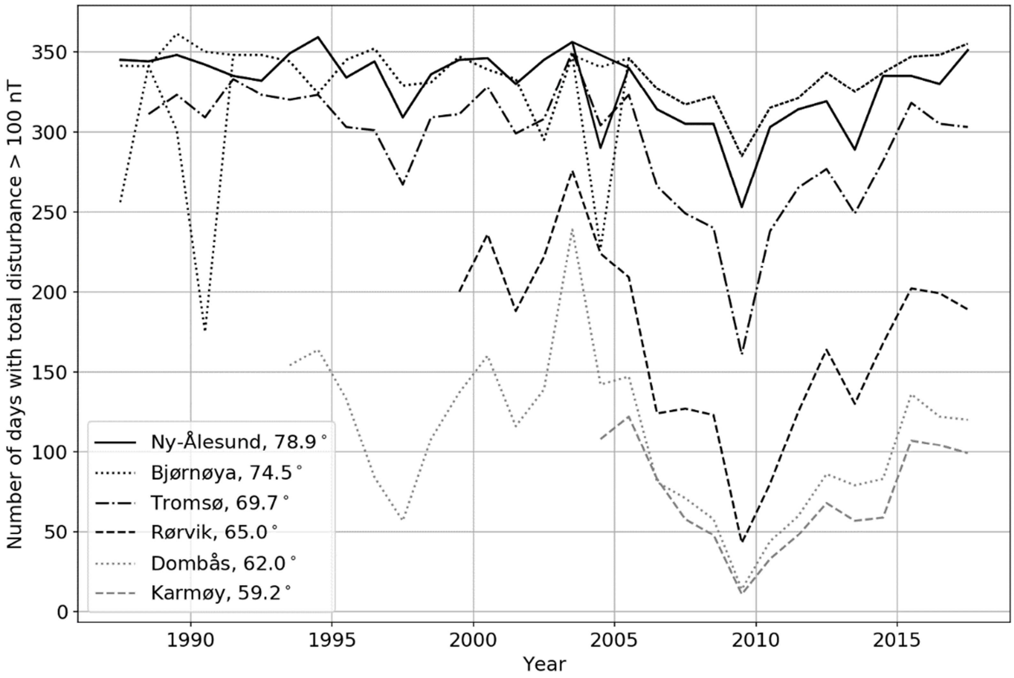

Figure 3. Number of days per year, for Northern Europe, where the solar-terrestrial interaction generates magnetic disturbances on the ground of more than 100 nT. Northern latitudes are more regularly exposed to magnetic disturbances, while the occurrence of disturbances in more southern latitudes are more correlated with the solar cycle (data from UiT).

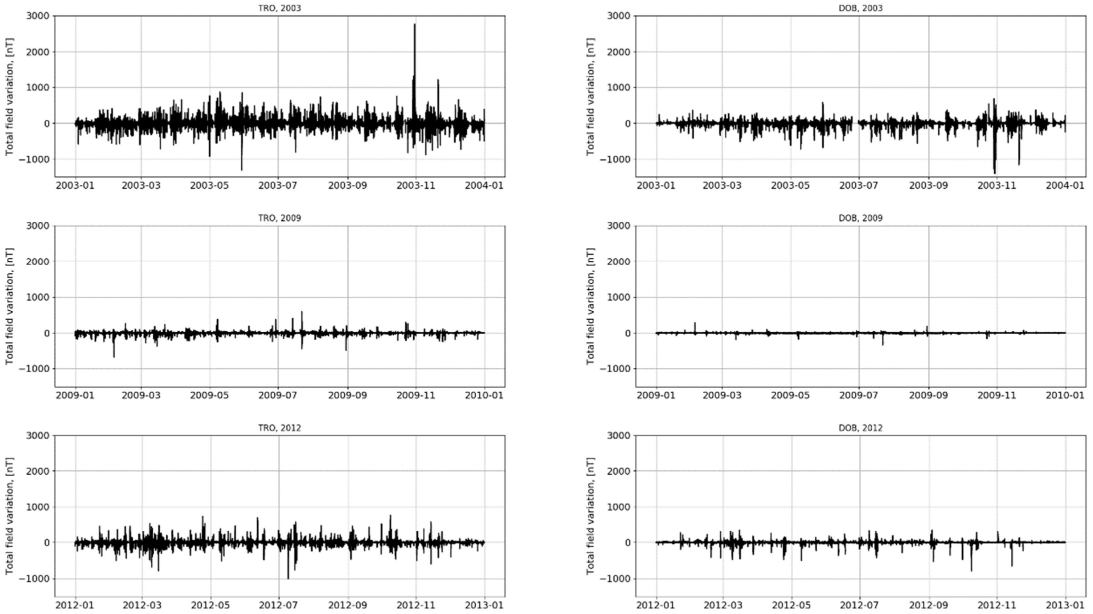

Figure 4. Total magnetic field variation on Tromsø (TRO; 70°N) and Dombås (DOB; 62°N) during a high disturbance (2003), calm (2009), and intermediate disturbance (2012) year.

The total field variation is calculated by subtracting the Earth's internal field from the measured total field strength. The internal field is estimated for every ten-day interval by finding the value of which most of the variations are centered around (using least square roots). Data from UiT.

2.2 Electric fields

In nature, electric fields are induced in the sea when saltwater, a conductor, moves in the natural magnetic field, and vary with the magnetic field strength and current speeds. For example, in the English channel electric fields usually measure 5 - 500 nV/cm (Kalmijn 1999). From the Atlantic Ocean, the Gulf Stream and the North Sea, similar electric field strengths of 350-500 nV/cm are reported (Buchanan et al. 2011). Magnetic disturbances induce electric fields both in the atmosphere and in the sea. During magnetic storms, induced electric fields can reach strengths of 10 000 nV/cm (Kalmijn 1999). Following the same principle, electric fields are also induced when animals swim in the Earth’s magnetic field (Kalmijn 1999).

Another source of natural electric fields is living organisms. Organisms constantly generate electric fields during their life processes for example during cell membrane transport, muscle contractions and nerve cell communication (Crampton 2019). The characteristics of the generated electric fields depend on the taxa, position and activity of the animal, and typically range from 2 000 – 100 000 nV/cm at a very close distance (Haine et al. 2001). Some fish also actively produce electricity (Crampton 2019). For example, some skates produce weak electric signals, presumably for communication, and electric rays hunt by generating electric discharges (Bratton and Ayers 1987, Bray and Hixon 1978, Lowe et al. 1994).

3. Magnetic fields and marine animals

3.1 Magnetosensitive organisms

Many organisms respond to geomagnetic cues, from bacteria (Frankel and Blakemore 1980) and protists (Bazylinski et al. 2000) to insects, crustaceans, fish, sea turtles, birds, and mammals (Wiltschko and Wiltschko 2005). Organisms respond to the direction, magnitude. or/and inclination of the geomagnetic field. There are three main mechanisms proposed for magnetoreception: magnetite based magnetoreception, radical-pair mechanisms and electric field mediated magnetic orientation. In the magnetite based magnetoreception, magnetite crystal alignment depends on the magnetic field, and is picked up by nerve cells. The radical-pair mechanism is based on chemical reactions dependent on the magnetic fields, and possibly coupled to photo excitation. Finally, electric fields are induced when the animal or saltwater move through the geomagnetic field, and could be used for orientation in electroreceptive organisms (Gould 2008, Johnsen and Lohmann 2005, Mouritsen 2018, Rommel and McCleave 1973, Walker et al. 2003). Although much remains to be learned, in the marine environment fish and turtles likely use a magnetite mechanism while the radical-pair mechanism has strong support (without excluding a magnetite mechanism) among birds and some invertebrates (Mouritsen 2018). All three mechanisms are extensively explained in reviews by Mouritsen (2018) and Johnsen and Lohmann (2005; 2008).

Animals can theoretically use magnetic cues to establish a direction of movement relative to the magnetic north (compass orientation) or, more complex, to orient on a magnetic map. In contrast to the establishment of a direction, a magnetic map sense utilizes two magnetic coordinates such as inclination and magnitude (or one magnetic gradient in combination with other environmental cues, e.g. stars, the sun, or polarized light) to position the organism in relation to its environment. A magnetic map sense requires high sensitivity to detect low gradients, as well as mechanisms to handle local irregularities, solar induced disturbances, and geomagnetic drift over time. In the marine environment there is, so far, evidence for a magnetic map sense in turtles, fish, and crustaceans (Mouritsen 2018). Magnetic orientation, on the other hand, is widespread in the aquatic environment, and has been related to both long distance migrations and local movements (Johnsen and Lohman 2008). In general, magnetic cues seem to be used interchangeably, or together with, other environmental cues (Freake et al. 2006, Muheim et al 2006).

Long distance migrations are common in the marine environment and many migratory species seem to use magnetic cues for orientation (Putman 2018; Mouritsen 2018). Both salmons and eels have lifecycles that include long distance migration at sea and respond to changes in the magnetic field. Among salmonid fish, geomagnetic orientation has been observed for both juveniles and adults. Sockeye salmon (*Oncorhynchus nerka*) spawners deviate their migration route towards the river following the geomagnetic drift (Putman et al. 2013). Further, fry or juveniles of sockeye salmon (Quinn 1980), chum salmon *(Oncorhynchus keta*; Quinn and Groot 1983), chinook salmon (*Oncorhynchus tshawytscha;* Walker et al. 2003), Atlantic salmon *(Salmo salar*; Scanlan et al. 2018)*;*brown trout (*Salmo trutta*; Formicki et al. 2002) and rainbow trout (Oncorhynchus mykiss; Chew and Brown 1989, Putman et al. 2014) - all migratory salmonid species - orient to manipulated magnetic fields. In experimental settings, European eels (*Anguilla anguilla)* and Japanese eels (*Anguilla japonica*) have responded to or oriented in relation to magnetic fields, indicating the possible use of a magnetic sense during marine migrations (Cresci et al. 2017, Durif et al. 2013, Nishi and Kawamura 2005, Nishi et al. 2004). Also yellowfin tuna (*Thunnus albacares*), another fish performing long distance migrations, have, in captivity, demonstrated the ability to discriminate shifts in the magnetic field direction in a training experiment (Walker 1984). Among displaced green turtles (*Chelonia mydas)*, magnetically manipulated individuals displayed longer homing paths compared to control animals, indicating that a magnetic sense facilitates homing (Luschi et al. 2007).

Elasmobranchs potentially use their electroreception and electric induction to sense magnetic fields (Molteno and Kennedy 2009). In directed movements, hammerhead sharks are hypothesized to orient in association with high magnitude magnetic slopes (Klimley 1993), and, similarly, several species of sharks swimming in straight lines for long periods of time are thought to do so using geomagnetic cues (Meyer et al. 2005). Indeed, in captivity, hammerhead (*Sphyrna lewini*) and sandbar sharks *(Carcharhinus plumbeus)* perceived the magnetic field in a conditioning experiment. The sharks were trained to respond to an artificial magnetic field by being presented food when this field was turned on (Meyer et al. 2005). Also captive stingrays *(Dasyatis brevicaudata)* have been able to discriminate between presence and absence of magnetic anomalies in training experiments (Walker et al. 2003). It cannot, however, be excluded that these elasmobranchs reacted to the electric field in the experimental coil rather than to the magnetic field (Johnsen and Lohmann 2005).

Cetaceans (whales and dolphins) have also been hypothesized to navigate using geomagnetic cues during their migrations. In line with this, sighting positions of fin whales (*Belaenoptera physalus)* of northeastern United States correlated with areas of low geomagnetic magnitude during migration, but not with bathymetric parameters, indicating the use of geomagnetic cues rather than bathymetric features for navigation (Walker et al. 1992). In captivity, bottlenose dolphins (*Tursiops truncates*), approached a magnetic object faster than to an identical non-magnetic object, indicating a magnetic sense (Kremers et al. 2014).

Magnetic cues can also be used to keep relatively weak swimming animals in suitable ocean currents, or in relation to movements to or away from the shore. Larvae of juvenile loggerhead turtles (*Caretta caretta)* presented with inclinations and intensities from different locations oriented in directions that would keep them in the North Atlantic gyre, their preferred feeding area (Lohmann et al. 2001, Lohmann and Lohmann 1996). Also Atlantic haddock larvae (*Melanogrammus aeglefinus*) oriented after the magnetic field, both in a chamber placed in the North Sea and in the laboratory, presumably as a mechanism for suitable dispersal (Cresci et al. 2019a). Glass eels (juvenile European eels) adjust their magnetic orientation depending on the tide and the moon phase to find their coastal habitats (Cresci et al 2017, 2019b, 2019c). In experiments, juvenile loggerhead sea turtles that leave the shore, swimming against the waves have been reported to use geomagnetic cues to maintain an off-shore direction after contact with the coast, has been lost (Goff et al. 1998). Similarly, Antarctic amphipods (*Gondogeneia antarctica*), brought to a laboratory, moved in the geomagnetic seaward direction of their home beach (Tomanova and Vacha 2016). Also in a laboratory, larvae of damselfish (*Chromis atripectoralis)* and cardinalfish (*Ostorhinchus doederleini*), two coral reef fishes, responded to shifts in magnetic field with corresponding shifts in orientation, demonstrating magnetic compass orientation and its potential use in homing or reef settlement (Bottesch et al. 2016, O'Connor and Muheim 2017).

At least some marine animals use the geomagnetic field for relatively local orientation. Spiny lobsters (*Panulirus argus*), for example, are capable of detecting changes and orienting in the magnetic field, and also have a magnetic map sense to guide their local movements (Boles and Lohmann 2003, Lohmann et al. 1995).

In general, our understanding of the use of magnetic cues among animals is limited, and its occurrence is likely more widespread than what is documented. For example, among marine invertebrates, sea slugs *(Nudibranchia)* orient relative to geomagnetic compass directions (Lohmann and Willows 1987) and several additional crustaceans are believed to use a magnetic compass (Kullnick 2000).

3.2 Magnetic disturbances and animal behavior

As discussed above, geomagnetic disturbances of different sizes are naturally recurrent, and correlate with changes in the movement pattern of both marine mammals and fish. Associations between live whale strandings and natural geomagnetic disturbances have been observed around the world (Ferrari 2017, Kirschvink et al. 1986, Klinowska 1986). Stranding locations of whales were associated with magnetic field anomalies of less than 50 nT (Kirschvink et al. 1986). Also, a publication in Russian reports a correlation between the level of geomagnetic activity and catches of herring. Herring supposedly migrated from shallow areas in the Barents Sea to deep waters of the Norwegian Sea during larger magnetic storms (references in Krylov et al. 2014).

Artificial displacement experiments can be used to infer changes of the magnetic field that may result in a changed orientation of groups of animals. In this kind of experiments, the magnetic field is manipulated by a coil system and the average orientation of animals are tested under different magnetic field conditions and in the absence of other orientational cues. In such experiments, Atlantic salmon showed distinct magnetic orientation from changes as small as 3400 nT and 6.4° (Scanlan et al. 2019), while spiny lobsters and loggerhead turtles both displayed distinct average orientation from artificial displacements around 5000 nT and 8° (Boles and Lohmann 2003, Fuxjager et al. 2011). Rainbow trout oriented in different direction from a displacement of 11 000 nT and 17° (Putman et al. 2014). The magnetic field differences that result in the animals changing orientation might indicate a size of disturbance that might cause an orientation effect in exposed animals. These levels, however, in addition to not being lower thresholds for inducing change, will in nature likely be modulated by other orientation cues (Freake et al. 2006, Muheim et al 2006, Mouritsen 2018)

Under water electrical cables cause local deviation from the natural geomagnetic field (Taormina et al. 2018). In the Baltic sea, migrating European eels passing over an electric cable, inducing magnetic field strengths of 5000 nT at 60 m distance, deviated from their migration route, but resumed their migration direction after only a short average delay of 30 minutes (Westerberg and Begout-Anras 2000, Öhman et al. 2007). In an enclosure experiment, little skate *(Leucoraja erinacea)* reduced speed, and increased distance, travel speed and frequency of turns – consistent with increased exploration or feeding behavior - when exposed to electromagnetic fields from an underwater cable. In this experiment the animals experienced magnetic fields strengths of 51 600 – 65 300 nT, or deviations from the natural field of 300 – 14 000 nT (Hutchison et al. 2018). In another experiment, edible crab (*Cancer pagaurus)* exposed to 2 800 000 – 40 000 000 nT for 24 h displayed increased sheltering and a preference for magnetically exposed shelters (Scott et al. 2018). However, no effects were found on the shelter seeking behavior of juvenile lobsters (*Homarus gammarus*) exposed to artificial magnetic field of a maximum intensity of 200 000 nT (Taormina et al. 2020).

Additionally, magnets have been used experimentally to modify fish behavior, for example to divert or attract certain species from/to fishing gears. Strong magnets have been used, with mixed results, to reduce shark bycatch in baited fisheries (Hart and Collin 2015, Porsmoguer et al. 2015, Richards et al. 2018), and in freshwater, magnets placed at the entrances of fyke-nets increased catches of perch (*Perca fluviatilis)*, roach (*Rutilus rutilus)*, rudd (*Scardinius erythrophthalmus*), and bleak (*Alburnus sp.*) (Formicki et al. 2004). In a behavioral choice experiment, magnets placed at artificial dens resulted in fewer sheltering spiny lobsters compared to controls, indicating that anthropogenic magnetic anomalies might influence local movement in natural environments (Ernst and Lohmann 2016)

Few studies are available on magnetic field thresholds perceived or susceptible of inducing a behavioral change in marine animals (But see table 1). Rainbow trout, in a heartbeat conditioning experiment, perceived magnetic field changes over 30 000 nT and 10° (Hellinger and Hoffmann 2009) and Japanese eels exhibited a response to 12 000 nT (Nishi et al. 2004). However, similar to the elasmobranch experiments referred to above, in these studies the experimental design did not allow to discriminate whether the animals responded to the magnetic field or changing electrical fields. As mentioned previously, in moving or changing systems the magnetic and electric fields occur together. This means that from a moving animal's perspective, or for an animal experiencing changing fields, the organism is simultaneously exposed to both magnetic and electric fields. Depending on the animal's perceptive ability, it could, in theory, sense neither, one, or both fields (Skiles 1985). This should be kept in mind here, and throughout the text when the use of separate electric and magnetic fields is discussed. It should also be noted that some experimental designs do allow the discrimination of non-magnetic effects: for example, systems that use doubled-wrapped coil systems with electricity running in antiparallel directions will cancel out the electric field (Kirschvink 1992).

As discussed above, organisms may respond to the direction and/or to the magnitude of the geomagnetic field. That is, they may orient along a simple compass direction, but they may also navigate using a 'magnetic map' based on the intensity and the inclination of the field (Johnsen and Lohmann 2005; Mouritsen 2018). Although little explored, this means that the geometry of the magnetic disturbance compared to the ambient geomagnetic field is likely important when evaluating its effect. Thus, the severity of a disturbance could vary between species that utilize different components of the magnetic field. For instance, if an organism senses direction in the horizontal plane, like a two-dimensional compass, then the horizontal component of the disturbance is key. It will be different for organisms sensing the vertical component or the inclination. The impact of the disturbance will also vary depending on its geometry, where both size and direction of the disturbance field compared to the ambient field will matter. A disturbance might also have greater effects on the inclination than on the total intensity, or vice versa. A compass sense might be affected differently than a map sense, or effects might differ if the map sense is fitted for local rather than long distance orientation (Johnsen and Lohmann 2005; Mouritsen 2018). Also, the physiological mechanisms by which an animal senses the magnetic field may modulate effects of anthropogenic disturbances. For example, strong and short electromagnetic pulses have been used to disable supposed magnetite based magnetic senses, while radiofrequency electromagnetic fields seem to immobilize the radical-pair mechanism (Johnsen and Lohman 2005; Mouritsen 2018). Hence, when assessing the impact of anthropogenic activity, it may be important to consider the particular way animals sense the field as well as the direction of the anthropogenic field compared to the ambient field.

Exposures to relatively high strength magnetic fields for days to weeks can have physiological effects on organisms. Formicki et al. (2019) reviewed effects on spermatozoa movement, fertilization rates, and egg incubation period in a range of fish species, and Juutilainen (2005) reports developmental effects in fish and sea urchin embryos from exposure to magnetic fields in the range of 0.1-10 mT. In addition, natural diurnal weak magnetic field variation could play a role in organisms' internal clocks, and magnetic disturbances may hence be able to cause chronobiological disruptions, with potential health consequences for the organism (Liboff 2014) and effects of anthropogenic magnetic fields on homeostatic and metabolic functions have been suggested (Begall et al. 2013). Also, distorted magnetic fields during developmental phases have resulted in failed magnetic orientation later in life, perhaps by effects on an internal magnetic map, in loggerhead sea turtles and rainbow trout (Fuxjager et al 2014, Putman et al. 2014). However, such long-term exposure effects are likely not relevant in the context of electromagnetic surveys which only disturb animals for a short period (minutes to hours).

4. Electric fields and marine animals

4.1 Electrosensitive organisms

Although all animals use electricity during their life-processes, some animals have also evolved to detect weak electric fields in their environment (Crampton 2019). Elasmobranchs detect very weak electric fields as the potential difference between the center of their body and their outer skin, across membranes lining sensory organs called Ampullae of Lorenzini. Ampullae are scattered over the head in sharks, and over the head and pectoral fins in skates and rays. Uneven stimulation of these ampullae enables detection of spatial location and direction of electrical sources. (Adair et al. 1998, Collin and Whitehead 2004). Among marine fish, specialized electroreception is also present among lampreys (*Petromyzontiformes*), stargazers (*Uranoscopidae*), sturgeons (*Acipenseridae*), catfishes (*Siluriformes*) and coelacanths *(Latimeriidae)* (Alves□Gomes 2001, Collin and Whitehead 2004, Walker 2001). In freshwater, paddle fish (*Polydon spathula),* lungfishes (*Dipnoi),* bichirfishes, reedfishes (*Polypteridae*), and weak electric fish (*Gymnotiformes* and *Mormyridae*) perceive weak electric fields (Crampton 2019; Wilkens and Hofmann 2007). In addition, Atlantic salmon and European eel respond to weak electric fields in the lab (Rommel Jr and McCleave 1973a). Electroreception has also recently been discovered in Guiana dolphin (*Sotalia guianensis*), and its presence in other cetaceans hypothesized (Czech-Damal et al. 2011).

4.1.1 Predation, predator avoidance, and communication

In elasmobranchs, the electric sense is used for prey detection, predator avoidance, communication with, and location of, conspecifics, and potentially for geomagnetic orientation (Bratton and Ayers 1987, Collin and Whitehead 2004). For example, in experiments, both skates and sharks detected and stroke at a burrowed plaice, as well as towards electrodes simulating a plaice, but failed to do so in the absence of electrical signals (Kalmijn 1971, Kalmijn 1982). Also, skate and shark embryos ceased all ventilation when exposed to electric fields simulating ventilation pulses of a typical predator, presumably to avoid predation (Kempster et al. 2013, Sisneros et al. 1998). Stingray males can detect buried females using electric cues, and their sensitivity increases during the reproductive season (Bodznick et al. 2003, Sisneros et al. 1998, Sisneros and Tricas 2000). Due to the low strength of bio-generated electrical signals, the detection distance is relatively short, in the range of 5 - 40 cm (Kalmijn 1971, Kalmijn 1982). There is also tendency for benthic feeding elasmobranchs to have enhanced electroreception compared to pelagic feeding fish within the same groups (Collin and Whitehead 2004, Raschi 1986). In freshwater also paddlefish and weak electric fish locate prey using their electric senses (Wilkens and Hofmann 2007).

4.1.2 Orientation and migration

As mentioned above, electrosensitive animals have been suggested to use their electric sense to orient according to electric fields induced by the geomagnetic field. In training experiments, stingrays showed the ability to orient relative to an electric field similar to those produced by ocean currents (Kalmijn 1982). Among teleosts, Atlantic salmon and American eel (*Anguilla rostrata)* showed, in heartbeat conditioning experiments – a training experiment to test detection ability, consistent cardiac response to weak electric fields. The electric field strengths were in magnitudes within the range predicted for the Gulf stream, causing speculation over the potential use of an electric sense in oceanic migration (Rommel Jr and McCleave 1973a, Rommel Jr and Mccleave 1973b).

4.2 Electric disturbances and animal behavior

There is some knowledge of threshold levels in relation to the electric field. Elasmobranchs can respond to electric fields of 1 – 10 nV/cm, but noise due to the fish moving in the geomagnetic field might put the practical threshold at 20 nV/cm (Collin and Whitehead 2004, Peters et al. 2007). Among non-elasmobranch fish, Russian sturgeon (*Acipenser gueldenstaedtii*) and sterlet (*Acipenser ruthenus)* showed behavioral responses to field strengths of 500 000 nV/cm (Basov 1999) whereas lampreys and eels in the laboratory were observed to perceive electrical field strengths down to 1000 nV/cm, and 670 nV/cm respectively (Chung-Davidson et al. 2004, Kullnick 2000, Rommel and McCleave 1972, Ronan and Bodznick 1986). Lamprey swimming and movement activity was affected differently by different electric field strengths (Chung-Davidson et al. 2004). In a training experiment, it was shown that the Guiana dolphin senses electric fields down to 4 600 nV/cm (Czech-Damal et al. 2011).

An interesting example of effects of electric field disturbance on fish behavior comes from juvenile paddlefish, a freshwater fish that can locate planktonic prey using their electric sense at up to 9 cm distance (0.5 to 1 body length for this fish). Paddlefish were observed during feeding in environments with different levels of anthropogenic electric field intensities. Fields magnitudes under 100 nV/cm had little effect on the feeding rates, whereas man-made fields above 1 000 nV/cm limited prey capture to plankton close to the fish's rostrum. At anthropogenic field intensities at 50 000 nV/cm, feeding nearly stopped (Wilkens et al. 2002). In addition, paddlefish also reacts to metallic objects, causing electro sensory overload, with clear avoidance (Wilkens and Hofmann 2007).

Artificial electric fields are used in electrofishing, causing local strong electric fields in the aquatic environment, followed by strong physio-behavioral effects in nearby animals. At increasing relatively high electric field strengths fish are first forcibly attracted towards the positive pole of the electric field (electrotaxis) and then stunned or paralyzed (electronarcosis) by the electric field (Bary 1956). These phenomena are used to catch fish in commercial and scientific electro fishing. 3.3 V/cm during 1 second, at 50 Hz is enough to stun herring. In Atlantic salmon, 2.5 V/cm for 6 - 12 s or 20 V/cm during 0.8 s stuns the fish. (Nordgreen et al. 2008, Roth et al. 2003, Snyder 2003). The stunning effects of the electric field on fish increases with fish size; 60 mV/cm is enough to paralyze a 75 cm shark, while at least 400 mV/cm is required for a 20 cm long mullet (Bary 1956, Smith 1974). Injury rates also depend on size. In an experiment related to electric trawling, juvenile cod (12 - 16 cm) survived 2.5-3 V/cm without visible injuries, while larger cod (41 - 55 cm) experienced vertebrate injuries at 0.4 – 1 V/cm (Soetaert et al. 2015). Also invertebrates are fished using electric fields. Razor clams (*Ensis spp.)* were stimulated to emerge from the sediment at field strengths of 0.5 V/cm, while 0.2 – 0.4 V/cm during 5 s stimulated Norway lobsters (*Nephrops norvegicus*) to emerge from burrows (Soetaert et al. 2015). Electric fields of 40-60 mV/cm (6 Hz) perpendicular to the body elicited a vertical movement response in brown shrimps

(*Crangon crangon)*. Fields parallel to the shrimps orientation resulted in higher thresholds, and 240 mV/cm elicited responses for all sizes and orientations (Polet et al. 2005).

Electric barriers uses electric fields to deter fish from specific areas (Noatch and Suski 2012). In waters with high occurrence of shark attacks on humans, electric fields have been used as a shark deterrent. In an experiment on scalloped hammerhead shark and leopard shark (*Triakis semifasciata*) motivated to feed, a mean electric field strength of 410 - 430 mV/cm caused head twitches in the fish, whereas an electric field strength of 960 - 1850 mV/cm resulted in the sharks retreating. In this study, the variability in response, however, was relatively high (Marcotte and Lowe 2008). In another study, based on net catches in relation to the electric barrier, 30 mV/cm appeared to keep sharks from crossing an electric barrier. Sharks were observed to approach but then retreat from the electrical barrier. (Smith 1974).

The characteristics of the electric field seem to be important in relation to fish's perceptions reactions. Elasmobranchs respond to changes in direct electric fields or to low frequency alternating fields between 0.1 – 10 Hz (Bodznick et al. 2003, Collin and Whitehead 2004, Kalmijn 1999), but this response is thought to be considerably reduced for frequencies above 5 Hz (Adair et al. 1998). Similarly, in freshwater, paddlefish primarily react to electric fields between 5 – 15 Hz, and European eel displayed a 20-fold increase in detection threshold when frequency was increased from 0.5 Hz to 50 Hz (Berge 1979). In tank experiments, Russian sturgeon and sterlet showed avoidance or foraging/searching behavior depending on the frequency with which the electric field alternated (Basov 1999). The directionality of stationary electric fields also seems to matter, at least for some species and under some circumstances. For example, American eel, in one heartbeat conditioning experiment, responded to a lower level when the electric field was applied perpendicular to the body, compared to when the field was applied in parallel to the fish body (Rommel and McCleave 1972), but European eel, in another experiment, did not (Berge 1979).

5. Effects of electromagnetic surveys on marine life

To our knowledge there are no published studies on effects of electromagnetic surveys on marine life. There is, nevertheless, as shown above, evidence of the importance of electric and magnetic cues in nature, some studies on how organisms are affected by specific levels of electric- or magnet field strengths, and established knowledge on natural variability of electric and magnetic field strengths.

The effects of electrical or magnetic fields generated by electromagnetic surveys on marine life likely depend on the strength and direction of the fields, duration of exposure, and detection capabilities of the animal. In theory, effects could be either physiological, in the form of injuries or mortality, or through behavioral changes in the animals. Both the electric and magnetic fields, however, attenuate quickly with distance. The magnetic fields created by an electromagnetic survey are below the magnitude of the Earth's geomagnetic field at 10 m from the source, and at the magnitude of relatively frequent geomagnetic storms at a couple of hundred meter. The electric field associated with these surveys, even at a very short range, is substantially weaker than what is required to stun fish, or cause sharks to retreat from an electric barrier (Fig. 2; Marcotte and Lowe 2008, Nordgreen et al. 2008, Roth et al. 2003). Similarly to the magnetic field, the electric field needs about 500 m to attenuate to natural oceanic field intensities (Buchanan et al. 2011, Johnsson and Oftedal 2011). Due to this quick attenuation of the field strengths, any mortality or injury effect that is limited to high fields strengths would be highly localized and, as the source is continuously moved around, short in duration. For example, according to an industry report on towed electric magnetic surveys, a single location along the towing line would be exposed to electric field intensities above 386 nV/cm for 21 min, and magnetic field intensities above 200 nT for only 14 min. (Buchanan 2011). Similarly, in vertical electromagnetic surveys, higher intensities at one point can persist for an hour before the source is moved. Hence, the risk of direct physical effects from the induced electric- and magnetic fields should be considered low. Maximum magnetic and electric field strengths generated by the electromagnetic surveys, however, are several times larger than the natural geomagnetic and electric fields, and above what causes behavioral effects in marine animals (Fig. 1-2; Table 1-2). Behavioral effects on magneto- and electro sensitive animals therefore cannot be excluded.

5.1 Potential behavioral effects of exposure to the magnetic field

As many different organisms perceive changes in the magnetic field, and can utilize magnetic information for orientation or navigation, electromagnetic surveys have the potential to temporarily distort magnetic cues and associated directed movements (Kirschvink et al. 1986, Westerberg and Begout-Anras 2000, Öhman et al. 2007). The artificial magnetic fields could constitute a problem for long distance, time constrained, migrating animals with revealed magnetic senses, such as eels (Durif et al. 2013) or salmonids (Putman et al. 2013), or even species such as cod (Godø 1995, Robichaud and Rose 2002, Rose 1993) or herring (Dragesund et al. 1997), which use unknown migratory cues. Also local movements can be disrupted by magnetic field disturbances. For example, among terrestrial animals, a higher proportion of honey bees (*Apis mellifera*) failed to find the hive when exposed to artificial magnetic fields and solar storms (Ferrari 2014) and homing pigeons were delayed by magnetic storms (Schreiber and Rossi 1978),). Magnetic gradients used for orientation may be small, and hence even small changes in the natural magnetic field caused by the artificial magnetic fields might disrupt local orientation. Also relatively small changes in orientation may cause the orienting animal to swim in the wrong direction or miss its target. This could, in theory, cause problems in for example homing lobsters (Boles and Lohmann 2003), juvenile turtles (Goff et al. 1998, Lohmann et al. 2001, Lohmann and Lohmann 1996), or landward orienting fish larvae and plankton (Bottesch et al. 2016, O'Connor and Muheim 2017, Tomanova and Vacha 2016). As small disruptions of the local magnetic field occur, and even vary, at one locality for a longer period of time (perhaps hours instead of minutes), and at a greater distance from the source, during electromagnetic surveys. These disruptions might have severe effects, at least on the individual animal, if affecting essential, time-restricted movements, such as finding protection from predation, or suitable and timely feeding areas for juvenile organisms.

Some animals calibrate their internal compass against other spatial cues (Cresci et al. 2019b, Goff et al. 1998, Muheim et al. 2006). If such calibration occur relatively seldom, disturbances during this time may be especially costly. Migratory songbirds (*Chatarus*), for example, calibrate their magnetic compass using the direction of the sunset or associated polarization patterns once a day (Cochran et al. 2004). Animals may also, as has been suggested for bluefin tuna (*Thunnus maccoyii*), use magnetic more intensive (dusk and dawn) or less disturbed (night) windows to obtain magnetic information with minimal influence of natural magnetic noise (Rodda 1984, Willis et al. 2009). Marine animals using such calibration windows, may end up moving in the wrong direction for a whole day, covering expansive distances and using valuable energy and time, if exposed to a distorted magnetic field during the time of calibration (Ferrari 2014, Vanselow et al. 2018). This would exacerbate the effect of the electromagnetic disturbance beyond the time of exposure.

As noted above, however, magnetic field variations are not uncommon in nature. In Norwegian waters animals experience from a few to hundreds of natural occurring magnetic disturbances (> 100 nT) per year, depending on latitude (Fig. 3) and time during the solar cycle. Disturbances commonly seen at high latitudes typically last from 30 min to 2 hours. Rarer, but larger, geomagnetic storms creating disturbances of the magnitude of several thousand nT, lasting for days, are also part of the natural geomagnetic landscape (Parkinson 1983). During an electromagnetic survey, one point in the sea is typically exposed to levels like these or higher for only a fraction of an hour (Buchanan et al. 2011). It is likely that many animals can handle this variation in the magnetic field, perhaps by recognizing temporary noise, and pause directed movements or rely on other environmental cues (Freake et al. 2006). As natural geomagnetic disturbances are much more common at higher latitudes, animals at lower latitudes could also be less used or adapted to, and hence worse at handling electromagnetic disturbances (Vanselow et al. 2018). High latitude animals, exposed to a higher rate of natural disturbances, may, on the other hand, be more dependent on the quiet periods between frequent natural disturbances. It has, for example, been suggested that animals, to avoid geomagnetic noise during daytime, utilize the magnetically more stable nights to establish orientation (Rodda 1984).

Lastly, in experiments, short but strong (4-5 ms; 40 – 500 mT) magnetic pulses have incapacitated the ability to orient after the magnetic field for a substantial period of time in such diverse taxa as logger head sea turtles (Irwin and Lohmann 2005), songbirds (Holland and Helm 2013, Wiltschko et al. 1994, Wiltschko et al. 1998), and bats (Holland et al. 2008). The inability to orient after the magnetic field lasted for 7-10 days after the exposure to the magnetic pulse (Holland and Helm 2013, Wiltschko et al. 1994, Wiltschko et al. 1998) It is believed that the short pulse alter the magnetization of magnetite particles involved in the magnetic sense of the exposed animal. For this to happen the pulse needs to be strong enough to re-magnetize the magnetic particles in the animal, and short enough so that the magnetic particles are unable to rotate in the magnetic field during the pulse (Irwin and Lohmann 2005, Wiltschko et al. 1998). In electromagnetic surveys, pulses are of longer duration and of lower magnitude than what was used in these experiments. Ferrari (2014), however, achieved similar delayed disorientation effects from a 80 seconds exposure to a 0.5 Hz magnetic field (200 μT) which is just within the range of what can be experienced by an animal exposed to electromagnetic surveys. The potential risk of such prolonged disabling of the magnetic sense from electric magnetic surveys remain highly speculative.

5.2 Potential behavioral effects of exposure to the electric field

While magnetic cues are used for orientation, electric cues are, at least among elasmobranchs, also used for feeding, avoiding predation, and social interactions (Collin and Whitehead 2004). Electric fields therefore have the potential to disrupt a wider range of behaviors. Elasmobranchs, and even eels, should be able to perceive signals from a typical electromagnetic survey at over a kilometer distance (Fig 3; Table 2; Buchanan et al. 2011, Peters et al. 2007). In theory, a perceived electric field could temporarily disrupt feeding, orientation, attention, or social interactions. For example, some elasmobranch species (Bakketeig et al. 2017, Pratt and Carrier 2001) gather in large mating or pupping aggregations. Disruption of these aggregations or related behaviors could potentially have detrimental effects on already threatened species (IUCN 2018).

Further, it is also not obvious to predict how electro-sensitive animals would react to an approaching and increasing electric field. A fluctuating and moving electric field of an electromagnetic survey does not necessarily translate directly to the relatively stable electric fields of an ocean current. Also, an electric signal could, depending on characteristics and context, affect fish behavior even if very weak (Grimsbø et al. 2014, Kalmijn 1999). In addition, and also not studied, it is possible that the sudden changes in electric fields, or magnetic fields, could cause escape responses, stress or changed feeding behavior extending beyond the duration of exposure, as seen in relation to acoustic noise from seismic surveys (Engås et al. 1996).

6. Conclusions

The electric and magnetic fields induced during electromagnetic surveys are within the scope of what is detectable by marine animals, and the generated fields will potentially affect the behavior of perceptive animals. As the electric and magnetic fields both attenuate rapidly, effects should be limited to within a few kilometers of the conducted survey. Exposures are also of relatively short duration, and the major part of the exposures consists of levels in the magnitude of regularly occurring natural electromagnetic disturbance. The lack of studies on effects on animal behavior is, however, a reason for concern. From available data, elasmobranchs seem to be the most electro-sensitive marine animals, and at highest risk of being disrupted by generated electric fields. Regarding the induced magnetic field, animals using magnetic cues for migration or local orientation during restricted time-windows might be most likely to be affected by an electromagnetic survey. This effect would be exacerbated if the exposure coincides with calibration of the animal’s magnetic compass or results in temporary retained disorientation. As a starting point, research efforts may focus on the effects of the survey induced electromagnetic fields on animal movement and orientation, and effects of the induced electric fields on elasmobranch behavior.

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9. Tables

Table 1. Observed behavioral effects of defined magnetic field strengths on marine animals. Distance is the modelled minimum distance to the electromagnetic source according to data from EMGS (Figure 1). Under frequency, the frequency of the electric field inducing the magnetic field in the laboratory is reported. Start means that it was a sudden onset of the artificial component of the magnetic field. Nature means that the values are based on associations with natural field intensities. Star (*) denotes field studies where the actual magnetic field detection has been deduced theoretically.

Group	**Taxa**	**Effect**	**Distance (m)**	**Field strength (nT)**	**Frequency**	**Reference**
Shark	*Sphyrnidae*	Navigate gradients*	>1000	0.04	Nature	Klimley 1993
Amphipod	*Gondogeneia antarctica*	Desorientation	>1000	2	976 Hz	Tomanova & Vacha 2016
Whale	*Odontoceti*	Disturbance correlated with strandings*	>980	<50	Nature	Kirschvink 1986
Salmonid	*Salmo salar*	Orientation shift (group of fish)	250	3400	Simulated	Scanlan et al. 2019
Turtle	*Caretta caretta*	Orientation shift (group of fish)	210	4900	Simulated	Fuxjager et al. 2011
Eel	*Anguilla anguilla*	Minor delay and course deviation*	210	5000 (@50m)	DC	Westerberg and Begout-Anras 2000
Lobster	*Panulirus argus*	Orientation shift (group of fish)	210	5100	Simulated	Boles and Lohmann 2003
Salmonid	*Oncorhynchus mykiss*	Orientation shift (group of fish)	130	11 000	Simulated	Putman et al. 2014
Eel	*Anguilla japonica*	Perception	120	12 600	Start	Nishi et al 2004
Skate	*Leucoraja erinacea*	Movement	110	14 000	60 Hz	Hutchison et al. 2018
Salmonid	*Oncorhynchus mykiss*	Perception	60	30 000	Start	Hellinger and Hoffman 2009
Crab	*Cancer pagaurus*	Attraction	Never	40 000 000	DC	Scott et al 2017

Table 2. Observed behavioral effects of defined magnetic field strengths on marine animals. Distance is the modelled minimum distance to the electromagnetic source according to data from EMGS (Figure 1). Under frequency, the frequency of the electric field inducing the magnetic field in the laboratory is reported. Start means that it was a sudden onset of the artificial component of the magnetic field. Nature means that the values are based on associations with natural field intensities. Star (*) denotes field studies where the actual magnetic field detection has been deduced theoretically.

Group	**Taxa**	**Effect**	**Distance (m)**	**Field strength (nV/cm)**	**Reference**
Elasmobranchs	*Elasmobranchii*	Response	>1000	1 - 20	Peters et al. 2007
Shark	*Scyliorhinus canicula*	Attraction	>1000	100	Gill and Taylor 2001
Eel	*Anguilla rostrata*	Perception	980	670	Rommel and McCleave 1972
Lamprey	*Petromyzontiformes*	Perception	890	1 000	Cited in Kullnick 2000
Dolphin	*Sotalia guianensis*	Perception	590	4 600	Czech-Damal et al. 2011
Eel	*Anguilla anguilla*	Perception	<10	470 000	Berge 1979
Sturgeon	*Acipenser spp.*	Avoidance or foraging	<10	500 000	Basov 1999
Shark	*Scyliorhinus canicula*	Avoidance	<10	1 000 000	Gill and Taylor 2001
Decapoda	*Crangon crangon*	Behavioral response	<10	40 000 000	Polet et al. 2005
Shark	*Sphyrna lewini; Triakis semifasciata*	Reaction	<10	42 000 000- 43 000 000	Marcotte and Lowe 2008
Shark	*Elasmobranchii*	Narcosis (75 cm fish)	<10	60 000 000	Smith 1974
Shark	*Sphyrna lewini; Triakis semifasciata*	Retreat	<10	90 000 000 - 185 000 000	Marcotte and Lowe 2008
Decapoda	*Neprhos norvegicus*	Emergence	<10	200 000 000	Stewart 1972, cited in Soetaert et al 2015
Mullet	*Mugilidae*	Narcosis (20 cm fish)	<10	240 000 000	Smith 1974
Bivalvia	*Ensis spp.*	Emergence	<10	500 000 000	Woolmer et al 2011

Highlights:

*Electromagnetic surveys generate electromagnetic fields to map petroleum deposits under the seabed with unknown consequences for marine animals.

* The electric and magnetic fields induced during electromagnetic surveys are within the scope of what is detectable by many marine animals.

* Animals using magnetic cues for migration or local orientation, especially during a restricted time-window, may be at greatest risk of being affected by electromagnetic surveys.

* In electrosensitve animals, anthropogenic electric fields could disrupt a range of behaviors, such as orientation, predation, predation avoidance, and communication.

*The lack of studies on effects of the electromagnetic fields induced by electromagnetic surveys on magneto- and electrosensitive animal behavior is a reason for concern.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: