A call to assess the impacts of electromagnetic fields from subsea cables on the movement ecology of marine migrants

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Abstract
The number of subsea cables in the marine environment is likely to grow substantially in the near future. Arrays of energy-generating windmills or wave power generators are planned for installation in the coastal waters of many countries worldwide. The electricity generated by these and other marine energy sources will be transported to shore through cables with the current and voltage creating electromagnetic fields (EMFs). Furthermore, there are also plans for the installation of undersea cables to interconnect countries and islands for the purpose of sharing power and communications. These also will generate EMFs in the marine environment. While shielding can negate the presence of direct electric fields, induced electric and magnetic fields readily penetrate into the water column. Cables carrying electric current produce anomalies in the earth’s main field, which could have the potential for disrupting the migrations of fishes and diverse marine animals that rely on magnetic cues for orientation or navigation. Studies designed to test how these anthropogenic magnetic fields disrupt magnetic orientation have only recently started to be conducted. Given the cultural, economic, and conservation value of many of the species potentially at risk, such work should be immediately prioritized.

KEYWORDS
EMF, migration, orientation

1 | THE EARTH’S MAGNETIC FIELD

Variation in the earth’s magnetic field is primarily due to two geologic sources, the main field and crustal anomalies (Kavet, Wyman, & Klimley, 2016; Klimley, 2013). The earth’s main magnetic field is generated by the circular convection of molten iron in the earth’s outer core 29,000 km from the surface of the earth (Figure 1). The strength of this field from this source decreases as a negative exponent with distance from the source. The total intensity of the magnetic field increases from roughly 30,000 nT at the equator, to 40,000–50,000 nT at the mid latitudes, and to 60,000 at the poles (Skiles, 1985). The inclination, or the angle between the total magnetic field and the earth’s surface, of the magnetic field is 0° at the
magnetic equator and 90° at the magnetic poles. There is abundant evidence that marine animals derive their direction and even geographic position from features in the main field (for comprehensive review, see Johnsen & Lohmann, 2008; Newton, Gill, & Kajiura, 2019). For instance, scientists have conducted experiments that indicate that yellow stingrays (*Urobatis jamaicensis*) can distinguish between the magnetic field intensity and inclination angle, the features of the main field that are necessary to form a bi-coordinate geomagnetic map (Newton & Kajiura, 2020a), and may have a polarity-based compass (Newton & Kajiura, 2020b). The second source of variation of the earth's magnetic field is due to local alterations (i.e., anomalies) to the dipole field caused by the extrusion of basalts containing magnetite, a mineral with single pole magnetic moment. These anomalies typically consist of gradients of 10–100 nT/km (Skiles, 1985). There are two sources of these localized alterations in the main field. First, molten basalts are extruded from the mantle at spreading centers to create the oceanic plates, where the magnetite within it orients to the axis and polarity of the earth's main field at the time of extrusion. The polarities of the magnetic particles in successive sections of the crust are either aligned parallel or anti-parallel to the current axis of the earth's dipole field due to the reversal of the earth's axis over geological time every 20,000–200,000 years (Skiles, 1985). The polarity reversals create bands of stronger and weaker magnetization oriented roughly in a north–south direction that are termed magnetic lineations. The strength of these local fields also decreases as a negative exponent, but as their source is nearer the surface, they increase more rapidly with depth than the main field (see upper right, Figure 1). The second source of localized alternations are molten basalts, which are extruded from the mantle during repeated volcanic eruptions. This process creates a dipole at a volcanic crater, due to the separation of basalts with magnetite parallel and antiparallel to the current axis of the main field (Vacquier & Uyeda, 1967), and magnetic minima (“valleys” in a topographic sense) and maxima (“ridges”) from the magnetite in lava flows leading away radially from their source (Klimley, 1993).

Evidence exists that marine animals use these magnetic gradients to guide themselves in the oceanic environment. The earth’s magnetic field produces compass, map, and topographic (i.e., topotaxis) information that can be used by animals to orient in a highly directional manner during migration. These different navigational tactics and strategies require different sensitivities to magnetic cues (and potentially use different mechanisms of magneto-sensation). A compass sense allows animals to determine directionality and maintain a heading. This can be derived via the polarity or inclination of the magnetic field and requires sensitivity only to the direction of field lines. Magnetic compasses are widespread throughout the animal kingdom (Wiltschko & Wiltschko, 2006). A magnetic map allows animals to derive large-scale spatial information from the magnetic field, for instance, allowing them to extrapolate position relative to a home or target field. Sensitivity to seemingly subtle changes in the magnitude of inclination angle and total intensity is required and diverse marine migrants such as spiny lobsters, sea turtles, European eels, and a variety of salmonids have been shown to use magnetic map cues for orientation (Putman, 2018). Recently, Keller et al. (2021) also demonstrated that the bonnethead (*Sphyrna tiburo*) uses magnetic cues for homeward orientation, strongly suggesting the presence of a magnetic map. In many instances, animals use a magnetic map and compass...
together—the map to assess where they are and the compass to maintain a heading toward their target (Boles & Lohmann, 2003). Animals can also use magnetic topotaxis to identify unique magnetic signatures associated with crustal anomalies as landmarks for guidance along migratory paths (Klimley, 1993). Though magnetic topotaxis has been less well studied in laboratory settings than magnetic compasses and maps, tracking data paired with measurements of magnetic topography imply that the known sensitivity to magnetic intensity in animals would, in many cases, allow precise orientation at relatively fine-scales.

2 | EXAMPLES OF NATURAL EMFS’ EFFECTS ON ANIMAL MOVEMENT

There have been different reasons proposed for the stranding of whales. One reason suggested for stranding and the death of multiple individuals of different cetaceans was the presence of infectious and parasitic diseases within their bodies, likely caused by human activity in their habitat (Diaz-Delgado et al., 2018). Another reason suggested for the deep diving Cuvier’s beaked whale (Ziphius cavirostris) is disorientation caused by the propagation of high levels of low and medium frequencies by the Low Frequency Active Sonar (LFAS) used to detect quiet diesel and nuclear submarines (Frantzis, 2004). Necropsies of eight of the stranded animals in the Kyparissiakos Gulf, Greece were performed, but no apparent abnormalities or wounds were found. Additionally, the proximity of military maneuvers were already suspected in causing mass stranding of Cuviers’ beaked whales off the Canary Islands (Simmonds & Lopez-Jurado, 1991; Vonk & Martin, 1989).

Stranding of whales have also been associated with temporal and spatial variation in the magnetic field. Granger, Walkowicz, Fitak, and Johnsen (2020) showed that gray whales (Eschrichtius robustus) are more likely to strand on days with relatively high levels of atmospheric radio-frequency noise, hypothesizing that this natural occurrence resulting from solar storms could disrupt their ability to perceive magnetic information. Stranding locations have been correlated with magnetic lineations that have rotated with plate movements so that the magnetic minimum intersect the coast. Such strandings are most common in Moray Firth and the Wash, located off the northeastern and southeastern coasts of Great Britain, respectively (Klimley et al., 2017). The degree of orientation, determined by applying the Rayleigh coefficient to measurements from a heading sensor placed on the sharks, was 0.999, where 1.0 would be perfectly straight and 0.0 would be in random (uniform) directions (Klimley, 1993). These movements were shown with a magnetic survey of the surrounding waters to be along magnetic maxima and minima leading away from the seamount. If magnetic topotaxis requires animals to closely and continuously sense magnetic gradients emanating from the seafloor, this navigational tactic may be particularly susceptible to disruption from EMF anomalies from undersea cables.

3 | EXAMPLES OF ANTHROPOGENIC EMFS’ EFFECTS ON ANIMAL MOVEMENT

There is evidence that EMF anomalies from cables affect the behavior of animals (Table 1). Mesocosm experiments demonstrate conspicuous increases in exploratory behavior and foraging in little skate (Leucoraja erinacea) and an increase in exploratory response in American lobster (Homarus americanus) within enclosures with an energized cable versus a nonenergized cable (Hutchison, Gill, et al., 2020). Silver-stage European eels (Anguilla anguilla) tracked in the Baltic Sea carrying coded ultrasonic tags swam more slowly in an area crossed by an energized cable than in areas where no cables occurred (Westerberg & Lagenfelt, 2008). Separately, eels carrying ultrasonic tags released distant from a cable and tracked by boat returned to their migratory direction with a delay of 30 min with their trajectories veering during passage over the cable (Öhman, Sigray, & Westerberg, 2007; Westerberg & Begout-Anras, 1999). The outmigration of Chinook salmon (Oncorhynchus tshawytscha) through San Francisco Bay was monitored based on their detection by automated receivers deployed in arrays across the Benicia, Richmond, Bay, and Golden Gate Bridges in San Francisco Bay before and after the installation of a direct-current transmission cable linking Pittsburg to San Francisco, California. The transmission line created anomalies near the Benicia Bridge, Richmond Bridge, and Bay Bridge in addition to those from the bridges (Klimley et al., 2017). The anomalies created by the cable and bridge are shown for the Richmond Bridge in Figure 2. After the cable was energized, higher proportions of fish crossed the cable and fish were more likely to be detected south of their normal migration route with
the times of transit through some regions reduced during cable activity (Wyman et al., 2018).

Indirect evidence of anthropogenic EMFs impacting marine animal movements also come from “magnetic displacement” experiments. In these studies, a carefully constructed array of coiled wires around an orientation arena is used to precisely manipulate the magnetic field around an animal. Typically, the magnetic fields presented to animals exist at some distant site, such as along their migratory route or at the edge of their typical range. Species like loggerhead sea turtles (Caretta caretta), European eel (Anguilla anguilla), and pink salmon (O. gorbuscha) will adopt headings that, had the animals been at the geographic location of the magnetic field, would guide them along their typical migratory route (Lohmann, Putman, & Lohmann, 2012; Naisbett-Jones, Putman, Stephenson, Ladak, & Young, 2017; Putman, Williams, Gallagher, & Dittman, 2020). The findings from these studies show that (a) specific components of the magnetic field are perceptible to animals, (b) demonstrate that this information is used for orientation, and (c) provide ecological context for the sensory ability (Putman, Ueda, & Noakes, 2019). Interestingly, in the context of anthropogenic EMFs, these studies also show that animals will spontaneously alter their orientation after relatively brief exposures (5–10 min) to relatively subtle changes (<5%) in magnetic intensity and inclination (Naisbett-Jones et al., 2017). Experiments in steelhead trout (O. mykiss) and loggerhead turtles further show that their ability to correctly respond to magnetic displacements is disrupted if exposed to anthropogenic magnetic fields that created unnaturally sharp gradients in the rearing environment (Putman, Meinke, et al., 2014; Putman, Scanlan, et al., 2014; Fuxjager et al., 2014). In both studies, whether the effect on magnetic navigation was permanent or diminished through time was not assessed.

| Species                     | Anthropogenic EMF                                                                 | Observed impact                                               | References                                                                 |
|-----------------------------|----------------------------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------------------|
| European eels (Anguilla anguilla) | Energized undersea cable, altering magnetic intensity by ~10%                    | Telemetered animals decreased swimming rates                  | Westerberg and Lagenfelt (2008)                                           |
| Chinook salmon (Oncorhynchus tshawytscha) | Energized underwater cable, altering magnetic intensity by ~10%              | Alterations to migratory routes and timing                | Klimley, Wyman, and Kavet (2017)                                           |
| Little skate (Leucoraja erinacea)  | Energized undersea cable under housing cage that distorted local field intensity by up to 27.2% | The presence of EMFs resulted in more exploratory activity       | Hutchison, Gill, Sigray, He, and King (2020)                                |
| American lobster (Homarus americanus) | Cable under rearing cage that distorted local field intensity by up to 27.2%        | The presence of EMFs resulted in more exploratory activity     | Hutchison, Gill, et al. (2020)                                             |
| Steelhead trout (Oncorhynchus mykiss) | Iron pipe near rearing tank, altering magnetic intensity by 24% and inclination angle by 12% | Fish failed to differentiate “magnetic displacements” in lab assays that show use of a magnetic map; controls did | Putman, Meinke, and Noakes (2014)                                          |
| Loggerhead Sea turtle (Caretta caretta) | Magnets placed around nests, altering magnetic intensity by a mean of 71% (range 23–564%) | Turtles failed to differentiate “magnetic displacements” in lab assays that show use of a magnetic map; controls did | Fuxjager, Davidoff, Mangiamele, and Lohmann (2014)                         |

FIGURE 2 Magnetic anomaly produced by the EMF from cable (vertical blue line) in San Francisco Bay leading from Pittsburg to San Francisco.
| Navigational behavior to assess | Species | Brief summary of relevant studies | References | Potential studies |
|--------------------------------|---------|----------------------------------|------------|-----------------|
| **Magnetic topotaxis**        | Scalloped hammerhead (*Sphyrna lewini*) | Trained to detect changes in the total magnetic field and shown to follow magnetic ridges in-situ | Klimley (1993); Meyer, Holland, and Papastamatiou (2005) | In-situ observation of animals carrying magnetometers nearby energized cables to document the potential effect of EMFs on fine-scale behavior |
|                                | Bonnethead (*Sphyrna tiburo*) | Demonstrated the presence of a map-like sense, orienting to target locations using magnetic cues | Keller et al. (2021) | Laboratory experiments using a Y-maze to investigate the effects of EMF of magnetic topotaxis for fine-scale behavior |
|                                | Yellow stingray (*Urobatis jamaicensis*) | Numerous studies demonstrating the species can discriminate between components of the magnetic field and likely has a polarity based compass | Newton and Kajiura (2020a, 2020b) | Laboratory experiments investigating the magnetic sensitivities of batoids to EMFs |
| **Magnetic map**               | European eels (*Anguilla anguilla*) | Glass eels demonstrated to have a magnetic map, detecting <5% changes in magnetic intensity and inclination angle | Naisbett-Jones et al. (2017) | Lab experiments to test impacts EMF exposures experienced by pelagic species and their ability to use a magnetic map for migration |
|                                | Spiny lobster (*Panulirus argus*) | Demonstrated to have a magnetic map | Boles and Lohmann (2003) | Lab experiments to test impacts EMF exposures experienced by benthic species and their ability to use a magnetic map for homing |
|                                | Loggerhead sea turtles (*Caretta caretta*) | Hatchling turtles demonstrated to have a fairly detailed, innate magnetic map based on magnetic intensity and inclination angle | See Lohmann et al. (2012) for review. | Lab experiments to test impacts EMF exposures experienced by surface-dwelling species and their ability to use a magnetic map for migration |
|                                | Chinook salmon (*O. tshawytscha*), Steelhead trout (*O. mykiss*), Pink salmon (*O. gorbuscha*), and Atlantic salmon (*Salmo salar*) | Juvenile salmon demonstrated to have an innate magnetic map (in Chinook salmon, this is shown to be based on use of both magnetic intensity and inclination angle) | Putman, Meinke, et al. (2014); Putman, Scanlan, et al. (2014); Putman et al. (2020); Scanlan, Putman, Pollock, and Noakes (2018); Minkoff, Putman, Atema, and Ardren (2020) | Lab experiments on juveniles to test impacts of EMF exposures experienced by anadromous species and their ability to use a magnetic map for migration. In-situ observation of older fish carrying magnetometers nearby energized cables to document the potential effect of EMFs on outmigration and homing behavior |

(Continues)
IDENTIFYING THE IMPACT OF EMFS ON ANIMAL ORIENTATION

Though sufficient to demonstrate the plausibility of impacts of EMFs on animal movements, generalizing information from the types of studies conducted to date is not yet possible (Hutchison, Secor, et al., 2020). Either studies were not designed to distinguish what aspect of the navigational system was being disrupted (e.g., Hutchison, Gill, et al., 2020) or the anthropogenic magnetic fields may not be directly relevant to those produced by undersea cables (e.g., Putman, Meinke, et al., 2014; Putman, Scanlan, et al., 2014). Additional studies, both in the field and laboratory, need to be completed to understand to what extent anthropogenic alterations to magnetic conditions in these animals’ habitats affect migrations (Table 2).

There are two general ways that anthropogenic EMFs could cause problems for animals attempting to navigate using magnetic cues: (a) EMFs might disrupt the ability of an animal’s magnetoreceptors to function (Engels et al., 2014) or (b) EMFs might cause the magnetic information detected by the animal to be unreliable or misleading (Putman, Meinke, et al., 2014; Putman, Scanlan, et al., 2014). Assessing impacts on magnetoreception would be difficult given that no magnetoreceptor has been definitively found in animals and thus a mechanistic understanding of how EMFs would disrupt that process cannot be satisfactorily established. In contrast, measuring the distortion of magnetic intensity, inclination, and declination over the areas occupied by cables and associated structures is quite feasible (Figure 1) and would yield valuable information as to what aspects of the magnetic navigation system of animals could be disrupted (Hutchison, Secor, et al., 2020). In either case, a key aspect of future work should be to investigate the functional implications of anthropogenic EMFs by assessing under what conditions they might alter movement patterns and, more specifically, limit the ability of animals to use magnetic cues for a map, a compass, or topotaxis.

We encourage field studies that rely on monitoring the movements of naturally migrating fish and other animals across power cables, such as those leading from arrays of wind-generating sources in the ocean. For these studies, species for which the natural path of migration is known should be prioritized to determine whether the installation of a cable affects the distribution and timing of movements. Particularly powerful to address this question would be to complete the following experiment. Individual animals in migratory condition carrying ultrasonic transmitters with accelerometer and magnetometer sensors could be tracked in a boat as they pass over
energized cables while recording telemetered measurements of the local magnetic field and other environmental conditions.

In tandem with field studies, laboratory experiments under controlled conditions should be carried out to investigate the magnitude and duration of exposure to EMFs from cables impact magnetic navigation. The paradigm of magnetic displacements, discussed above, would likely be particularly powerful to assess EMFs effects on the magnetic map and compass (Putman, 2018). Experiments could be conducted in which animals are exposed to EMFs (like those associated with undersea cables) for different lengths of time and then tested in magnetic displacements over a range of recovery periods to determine what level of exposures impact magnetic orientation and for how long. To assess impacts on magnetic topotaxis, the ability for animals to be conditioned to follow either magnetic minima or maxima (produced by alternately energized cables, perhaps in separate arms of a Y-maze) should be investigated with and without the addition of EMFs. With such experiments in the lab and the field focusing on a few key model species, it would be possible to make predictions about how a variety of animals that use magnetic cues for similar navigational tasks would likely be impacted by anthropogenic EMFs. With data from these empirical approaches, the effect of EMFs from cables and the associated infrastructure that are proliferating across coastal areas throughout the world can be determined on a population- and ecosystem-level for marine animals (Putman, 2018).

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REFERENCES
Avens, L., & Lohmann, K. J. (2003). Use of multiple orientation cues by juvenile loggerhead sea turtles Caretta caretta. The Journal of Experimental Biology, 206, 4317–4325.
Avens, L., & Lohmann, K. J. (2004). Navigation and seasonal migratory orientation in juvenile sea turtles. The Journal of Experimental Biology, 207, 1771–1777.
Boles, L. C., & Lohmann, K. J. (2003). True navigation and magnetic maps in spiny lobsters. Nature, 421, 60–63.
Cresci, A., Paris, C. B., Durif, C. M., Shema, S., Bjelland, R. M., Skiftevik, A. B., & Brownm, H. I. (2017). Glass eels (Anguilla anguilla) have a magnetic compass linked to the tidal cycle. Science Advances, 3(6), e1602007.
Diaz-Delgado, J., Fernandez, A., Sierra, E., Sacchini, S., Andrada, M., Vela, A. I., ... Arbelo, M. (2018). Pathologic findings and causes of death of stranded cetaceans in the Canary Islands (2006-2012). PLoS one, 13(1), e0204444.
Durif, C. M., Browman, H. I., Phillips, J. B., Skiftevik, A. B., Vollstedt, L. A., & Stockhausen, H. H. (2013). Magnetic compass orientation in the European eel. PLoS ONE, 8(3), e59212.
Engels, S., Schneider, N. L., Lefeldt, N., Hein, C. M., Zapka, M., Michalik, A., ... Mouritsen, H. (2014). Anthropogenic electromagnetic noise disrupts magnetic compass orientation in a migratory bird. Nature, 509(7500), 353–356.
Frantzis, A. (2004). The first mass stranding that was associated with the use of active sonar (Kyparissiakos gulf, Greece, 1996). In Evans P.G.H. & Miller, L.A. (Eds.) Proceedings of the Workshop on Active Sonar and Cetaceans, ECS Newsletter 42, pp. 14–20.
Fuxjager, M. J., Davidoff, K. R., Mangiamele, L. A., & Lohmann, K. J. (2014). The geomagnetic environment in which sea turtle eggs incubate affects subsequent magnetic navigation behaviour of hatchlings. Proceedings of the Royal Society B: Biological Sciences, 281(1791), 20141218.
Goff, M., Salmon, M., & Lohmann, K. J. (1998). Hatching Sea turtles use surface waves to establish a magnetic compass direction. Animal Behaviour, 55(1), 69–77.
Granger, J., Walkowicz, L., Fitak, R., & Johnsen, S. (2020). Gray whales strand more often on days with increased levels of atmospheric radio-frequency noise. Current Biology, 30, R155–R156.
Herrnkind, W. F., & McLean, R. (1971). Field studies of homing, mass emigration, and orientation in the spiny lobster, Panulirus argus. Annals of the New York Academy of Sciences, 188, 359–376.
Hutchison, Z. L., Gill, A. B., Sigray, P., He, H., & King, J. W. (2020). Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. Scientific Reports, 10, 4219.
Hutchison, Z. L., Secor, D. H., & Gill, A. B. (2020). The interaction between resource species and electromagnetic fields associated with electricity production by offshore wind farms. Oceanography, 33(4), 96–107.
Johnsen, D., & Lohmann, K. J. (2008). Magnetoreception in animals. Physics Today, American Institute of Physics, 61, 29–35.
Kavet, R., Wyman, M. T., & Klimley, A. P. (2016). Modeling magnetic fields from a DC power cable buried beneath San Francisco Bay based on empirical measurements. PLoS one, 11, 1–21.
Keller, B. A., Putman, N. F., Grubbs, R. D., Portnoy, D. S., & Murphy, T. (2021). Map-like use of earth’s magnetic field in sharks. Current Biology, 31, 1–6.
Kirschvink, J. L., Dizon, A. E., & Westphal, J. A. (1986). Evidence from strandings for geomagnetic sensitivity in cetaceans. The Journal of Experimental Biology, 128, 1–24.
Klimley, A. P. (1993). Highly directional swimming by scalloped hammerhead sharks, Sphyrna lewini, and subsurface irradiance, temperature, bathymetry, and geomagnetic field. Marine Biology, 117, 1–22.
Klimley, A. P. (2013). Sense of electromagnetic fields: Electro-reception/magnetoreception. In Biology of sharks and rays. Chicago: University of Chicago Press.
Klimley, A. P., Wyman, M. T., & Kavet, R. (2017). Chinook salmon and green sturgeon migrate through large distortions in the local magnetic field produced by bridges. PLoS One, 12, 1–16.
Klinowska, M. (1985). Cetacean live stranding sites relate to geomagnetic topography. Aquatic Mammals, 1, 27–32.

Lohmann, K. J. (1991). Magnetic orientation by hatching loggerhead sea turtles (Caretta caretta). The Journal of Experimental Biology, 155(1), 37–49.

Lohmann, K. J., Petchef, N. D., Nevitt, G. A., Stetten, G., Zimmer-Faust, R. K., Jarrard, H. E., & Boles, L. C. (1995). Magnetic orientation of spiny lobsters in the ocean: Experiments with undersea coil systems. The Journal of Experimental Biology, 198, 2041–2048.

Lohmann, K. J., Putman, N. F., & Lohmann, C. M. (2012). The magnetic map of hatching loggerhead sea turtles. Current Opinion in Neurobiology, 22(2), 336–342.

Meyer, C. G., Holland, K. N., & Papastamatiou, Y. P. (2005). Sharks can detect changes in the geomagnetic field. Journal of the Royal Society Interface, 2, 129–130.

Minkoff, D., Putman, N. F., Atema, J., & Ardren, W. R. (2020). Non-anadromous and anadromous Atlantic salmon differ in orientation responses to magnetic displacements. Canadian Journal of Fisheries and Aquatic Sciences, 77(11), 1846–1852.

Naisbett-Jones, L. C., Putman, N. F., Stephenson, J. F., Ladak, S., & Young, K. A. (2017). A magnetic map leads juvenile European eels to the Gulf stream. Current Biology, 27(8), 1236–1240.

Newton, K. C., Gill, A. B., & Kajitura, S. M. (2019). Electroreception in marine fishes: Chondrichthyans. Journal of Fish Biology, 95, 135–154.

Newton, K. C., & Kajitura, S. M. (2020a). The yellow stingray (Urobatis jamaicensis) can discriminate the geomagnetic cues necessary for a bi-coordinate magnetic map. Marine Biology, 167, 1–13.

Newton, K. C., & Kajitura, S. M. (2020b). The yellow stingray (Urobatis jamaicensis) can use magnetic field polarity to orient in space and solve a maze. Marine Biology, 167, 36.

Öhman, M. C., Sigray, P., & Westerberg, H. (2007). Offshore windmills and the effects of electromagnetic fields on fish. AMBIO: A Journal of the Human Environment, 36, 630–633.

Putman, N. F. (2018). Marine migrations. Current Biology, 28, R972–R976.

Putman, N. F., Meinke, A. M., & Noakes, D. L. (2014). Rearing in a distorted magnetic field disrupts the ‘map sense’ of juvenile steelhead trout. Biology Letters, 10(6), 20140169.

Putman, N. F., Scanlan, M. M., Billman, E. J., O’Neil, J. P., Couture, R. B., Quinn, T. P., ... Noakes, D. L. (2014). An inherited magnetic map guides ocean navigation in juvenile Pacific salmon. Current Biology, 24(4), 446–450.

Putman, N.F., Ueda, H. & Noakes, D.L. (2019). The current status of research on geomagnetic navigation in Pacific salmon. North Pacific Anadromous Fish Commission Technical Report No. 15, pp. 182–186.

Putman, N. F., Williams, C. R., Gallagher, E. P., & Dittman, A. H. (2020). A sense of place: Pink salmon use a magnetic map for orientation. The Journal of Experimental Biology, 223(4), jeb218735.

Scanlan, M. M., Putman, N. F., Pollock, A. M., & Noakes, D. L. (2018). Magnetic map in nonanadromous Atlantic salmon. Proceedings of the National Academy of Sciences, 115(43), 10995–10999.

Simmonds, M. P., & Lopez-Jurado, L. F. (1991). Whales and the military. Nature, 351, 448.

Skiles, D. D. (1985). The geomagnetic field: Its nature, history, and biological relevance. In J. S. Kirschvink, D. S. Jones, & B. J. MacFadden (Eds.), Magnetite biomineralization and Magnetoreception in organisms (pp. 43–102). New York: Plenum Press.

Tomanová, K., & Vácha, M. (2016). The magnetic orientation of the Antarctic amphipod Gondogenea Antarctica is cancelled by very weak radiofrequency fields. The Journal of Experimental Biology, 219(11), 1717–1724.

Ugolini, A., & Pezzani, A. (1995). Magnetic compass and learning of the Y, axis (sea-land) direction in the marine isopod Idotea baltica basteri. Animal Behaviour, 50(2), 295–300.

Vacquier, V. & Uyeda, S. (1967). Palaeomagnetism of nine seamounts in the western Pacific and of three volcanoes in Japan. Bulletin of the Earthquake Research Institute, 45, 315–348.

Vonk, R. & Martin, V. (1989). Goosed beaked whales Ziphius cavirostris mass strandings in the Canary Islands. In P.G. Evans & H. Smeenk (Eds.), European Research on Cetaceans, (pp. 73–77), Proceedings of 3rd Annual Conference ECS, La Rochelle, European Cetacean Society, Lieden.

Westerberg, H. & Begout-Anras, M.L. (1999). Orientation of silver eel (Anguilla anguilla) in a disturbed geomagnetic field. In A. Moore & I. Russell (Eds.). Proceedings of 3rd Conference on Fish Telemetry in Europe, Norwich.

Westerberg, H., & Lagenfelt, I. (2008). Sub-sea power cables and the migration behaviour of the European eel. Fisheries Management and Ecology, 15, 369–375.

Wiltshko, R., & Wiltshko, W. (2006). Magnetoreception. BioEssays, 28, 157–168.

Wyman, M. T., Klimley, A. P., Battleson, R., Agosta, T., Chapman, E., Haverkamp, P. J., ... Kavet, R. (2018). Impacts of an underwater high voltage DC power cable on salmon. Marine Biology, 165, 134–158.

How to cite this article: Klimley AP, Putman NF, Keller BA, Noakes D. A call to assess the impacts of electromagnetic fields from subsea cables on the movement ecology of marine migrants. Conservation Science and Practice. 2021; 3:e436. https://doi.org/10.1111/csp2.436