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LIST OF ABBREVIATIONS

AC	Alternating current
COWRIE	Collaborative Offshore Wind Research into the Environment
DC	Direct current
DON	Dorsal octavolateralis nucleus
EIA	Environmental impact assessment
EF	Electric field
emf	Electromotive force
EMF	Electromagnetic field
HVAC	High voltage alternating current
HVDC	High voltage direct current
LFAC	Low frequency alternating current
ORED	Offshore renewable energy development
TPES	Total primary energy supply

CHAPTER ONE:

GENERAL INTRODUCTION

1.1 Introductory overview

As concerns over anthropogenically-driven climate change continue to rise, there is increasing interest in the exploitation of renewable energy sources as an alternative to fossil fuels. Many land-based renewable energy options have already been developed, so marine-based energy sources, such as tidal turbines and offshore wind farms, will become increasingly important in meeting future energy requirements. Consents for offshore renewable energy developments (OREDs) must consider the potential ecological impacts of various aspects of the development, including construction, operational noise and the electromagnetic fields (EMFs) associated with electrical equipment and power cables in a seawater environment and the effects of all of these on marine life. This thesis concentrates on the important and currently understudied question of possible impacts from EMFs associated with power transmission from such developments on elasmobranchs. Elasmobranchs are known for their extremely sensitive electrosensory system and are thus likely to be affected by anthropogenic EMFs. The current lack of studies which investigate such potential impacts must be addressed in order to conduct accurate environmental impact assessments (EIAs) and inform effective legislation as these marine resources are developed.

1.2 The role of marine sources in meeting renewable energy demands

1.2.1 Fossil fuels and climate change

Over the past century, the increasing demand for energy due to technological advances and availability has driven an exponential increase in the use of fossil fuels. However, this rapid growth in the extraction and use of fossil fuels has come at an environmental cost on a global scale. There is strong evidence of links between the increasingly high levels of carbon dioxide emissions as a result of burning fossil fuels for energy and climate change (Chow, *et al.*, 2003; Doney, *et al.*, 2009). As a result of anthropogenically-driven climate change, increased climatic variability is expected and global temperatures are predicted to rise by 3-5°C within the next 50 years (Gill, 2005; Hulme, 2005). The future impacts of such changes are hotly debated, but with evidence of changes in species distributions and ranges as a result of changing climate already happening, there is little doubt that ecosystems will be affected (Walther, *et al.*, 2002; Pearson & Dawson, 2003). Climate change will also affect agricultural productivity and availability of resources, which will both impact on human welfare (Chow, *et al.*, 2003).

The worldwide demand for energy, particularly in the form of electricity, continues to increase, driven by the rising availability and demand for consumer electronics, a phenomenon intensified by the broadening access to such commodities in developing countries, and the energy requirements of associated production industries (Pelc & Fujita, 2002; Freris & Infield, 2008). In 2013, 81.4% of the global total primary energy supply (TPES) was derived from fossil fuels, *i.e.* – petroleum, natural gas and coal (IEA, 2015). Whilst it is estimated that there are currently enough untapped fossil fuel reserves to sustain increasing energy demands for at least several decades, the higher costs of prospecting for and extracting less accessible reserves are likely to continue driving energy prices upwards (Chow, *et al.*, 2003).

1.2.2 Moving towards renewable energy

The combination of rising energy prices and the environmental degradation associated with greenhouse gas emissions from the use of fossil fuels has prompted an interest in finding ways of generating electricity from renewable sources (Pimentel, *et al.*, 2002; Gill, 2005). Renewable energy, or energy harnessed from “natural” sources, such as wind and tidal energy, has become an attractive alternative for countries trying to reduce their dependency on fossil fuels and cut their greenhouse gas emissions.

Consequently, increasing numbers of renewable energy projects are being proposed (Gill, 2005). However, though renewable energy sources are usually "cleaner" than fossil fuels, they still have environmental impacts. Indeed, no source of energy can ever be impact-free.

Whilst hydropower is largely the most common form of renewable energy – 16.3% of global electricity demands in 2013 were supplied through hydropower, compared to 5.7% for all other renewable sources combined – offshore renewable energy developments (OREDs) such as offshore wind farms or tidal turbines are becoming more prevalent as part of this overall proliferation of renewable energy project proposals (O'Rourke*, et al.*, 2010; Normandeau*, et al.*, 2011; IEA, 2015). However, the increase in OREDs has not been matched by a comparable increase in research into the ecological impacts of these developments (Gill, 2005).

1.2.3 Hydropower and its limitations

At the most basic level, the generation of hydropower simply involves harnessing some of the energy of water flowing downhill to drive a turbine which, in turn, will generate electricity. Dams are often used in order to maximise the power that can be exploited and thus the electricity that can be generated, which also allow for the control of how much water is released. Globally, hydropower is the most widely-used renewable energy with at least 160 countries making use of it in some capacity. It is also one of the few renewable energy technologies that offer the potential of energy storage in the form of additional reservoir lakes. During periods of low demand, water can be pumped up to the reservoirs and stored, then released when a spike in electricity generation is required (Schiermeier*, et al.*, 2008).

A number of major environmental impacts are associated with hydropower, particularly in the case of large dams. Aside from the obvious ecological losses sustained by permanently flooding the river valley behind a dam, alteration of the river's natural flow rates also have effects, particularly in terms of changes in sediment deposition (Renöfält*, et al.*, 2010). Dams can also affect the reproduction of fish species that swim upriver to spawn, such as salmon, even with mitigation measures in place (Ugedal*, et al.*, 2008).

1.2.4 Wind energy and its limitations

Wind energy is harnessed through the use of wind turbines, usually grouped together into large wind farms. Whilst technological advances have vastly improved the efficiency of turbines, the variable nature of wind means that on average, wind farms only produce around 20% of their potential capacity. The changeable and unpredictable nature of wind also means that energy will not always be generated when required. Until reliable energy storage solutions are developed, wind energy cannot be a steady source of energy (Schiermeier*, et al.*, 2008).

Due to the low power density of wind, wind farms require large areas of land, and consequently tend to have quite a heavy visual impact on the landscape. As a result, proposals have not always met with public support which often places high value on the landscape aesthetics (Schiermeier*, et al.*, 2008; Graham*, et al.*, 2009). In addition, wind turbines have been associated with higher bird mortalities, particularly when located on migratory routes (Barrios & Rodríguez, 2004). Offshore wind farms are becoming increasingly popular, given the generally windy conditions, large amounts of space and lack of complaints about the visual impact (Gill, 2005). However, offshore wind farms have also been shown to affect and increase mortality in certain marine bird species (Garthe & Hüppop, 2004).

1.2.5 The expansion and potential of tidal energy

There are currently two main methods of harnessing energy from tidal sources: turbines or barrages. A tidal barrage is effectively a dam across the mouth of an estuary, but it is constructed such that water can flow through the barrage in both directions, even though barrages generally only harness the energy of the water flowing out of the estuary as the tide ebbs. Tidal turbines follow a similar concept to wind turbines but are completely submerged and driven by the tidal water flow through a channel (Pelc & Fujita, 2002; O'Rourke, *et al.*, 2010).

The technology for both tidal turbine and barrage construction is available and tidal barrages are in place at several sites around the world (Freris & Infield, 2008; O'Rourke, *et al.*, 2010). The tidal barrage at La Rance in France has been operating since the early 1960s, and other barrages around the world include Annapolis in Canada and Jiangxia in China, which were both built in the early 1980s (Hammons, 1993; O'Rourke, *et al.*, 2010). However, such projects generally have very high set-up costs and can have a payback period of several decades, limiting their financial attractiveness. Consequently, tidal energy has not been explored as much as other renewable energy options (O'Rourke, *et al.*, 2010).

Tide times and heights are accurately predictable, so the energy production from tidal sources can be reliably forecast which is a distinct advantage of tidal energy in comparison to some other sources of renewable energy, such as wind. Another advantage of tidal energy is that the water flow that drives the turbines generally exhibits less fluctuation than wind speeds and so electricity production is more consistent over a period of time (Freris & Infield, 2008; O'Rourke, *et al.*, 2010).

However, the peak times of tidal energy generation obviously do not always coincide with the hours of peak demand for electricity. Whilst it would theoretically be possible to level out the diurnal variability in electricity generation by setting up tidal energy projects at sites with tidal cycles that are out of phase with each other, such sites are not necessarily available. Changes in tidal ranges as a result of neap and spring cycles would not be offset by the use of multiple sites as they would likely all be affected by the same spring-neap tidal cycle (Freris & Infield, 2008).

Unsurprisingly, the environmental impact of tidal barrages can be significant, as estuarine environments are generally sensitive habitats and already under intense anthropogenic pressure. Loss of nursery grounds, habitat reduction, alterations of salinity levels, changes in sediment deposition and the consequent changes in the estuarine communities have all been associated with tidal barrages (Pelc & Fujita, 2002; Kadiri*, et al.*, 2012). Tidal turbines are considered to have a significantly lesser negative environmental effect, with the greatest likely impacts associated with the construction and decommissioning phases of projects, although there has been limited research into this (Pelc & Fujita, 2002; Simmonds & Brown, 2010). During the operational phases of projects, noise, electromagnetic fields around cables and the possibility of collision by marine organisms with the turbines are the three main potential issues, all of which may have indirect effects on species composition and food availability in the surrounding area or impact on migration routes of marine organisms (Gill, 2005; Simmonds & Brown, 2010).

Tidal energy is currently limited to being used in conjunction with other sources of energy generation, whether renewable or not, to cover shortfalls in energy production at slack tides. The development of large-scale energy storage solutions would minimise some of the energy loss that currently results from strong tidal cycles at times of low-peak demand and also provide additional energy at times of high demand, which would make tidal energy a more effective and reliable source of renewable energy (Freris & Infield, 2008; Mason*, et al.*, 2010). Rising energy costs are also likely to eventually make tidal energy projects more financially viable and tidal energy may become a more attractive renewable energy option, regardless of environmental impacts (Freris & Infield, 2008; O'Rourke*, et al.*, 2010). Consequently, in order to develop such resources in as environmentally-sensitive a manner as possible, a greater understanding of what some of these impacts may be is necessary (Normandeau*, et al.*, 2011; Gill*, et al.*, 2014).

1.3 New Zealand as a specific case in the drive for marine-based renewable energy

The latest available data on energy usage in New Zealand is for 2014, during which renewable energy made up 39.5% of New Zealand's TPES, the third highest proportion of TPES from renewable energy in the world. Looking at just electricity generation, 79.9% of New Zealand's electricity came from renewable energy sources, predominantly hydropower and geothermal (MoBIE, 2015). Whilst New Zealand projects an image of itself as a "clean and green" country, it is currently heavily reliant on fossil fuels for transport and was the fifth highest per capita greenhouse gas emitter in 2010, largely due to the strong agricultural component of its economy (Krumdieck, 2009; Schaefer, *et al.*, 2012).

The coalition that governed New Zealand from 1999-2008, had made an ambitious commitment to renewable energy and had been aiming for 90% of the country's electricity generation to be met by renewable sources by 2025. Following the 2008 elections, this target has been maintained by the government, which is still in power, which also announced they would consider aiming to reduce greenhouse gas emissions to 10-20% below pre-1990 levels by 2020 (Krumdieck, 2009; Mason, *et al.*, 2010; Schaefer, *et al.*, 2012).

In 2014, hydropower, geothermal and wind energy made up 71.4%, 20.3% and 6.5%, respectively, of New Zealand's renewable electricity production (MoBIE, 2015). There is limited scope for the expansion of hydropower-based energy production, since most suitable sites for large-scale projects have already been developed. There are still several geothermal sites that have the potential to be developed (Mason, *et al.*, 2010). Proposals for large-scale wind farms have generally received limited public support resulting in protracted consent processes, though this may change with increasing awareness of and concern over the impacts of climate change. A number of projects have also met financial difficulties (Kelly, 2011; Schaefer, *et al.*, 2012). Currently in New Zealand, tidal energy is the least-developed renewable energy resource.

1.3.1 Case study: The Kaipara Marine Turbine Generation Project

The Kaipara Harbour, on the north-western coast of New Zealand's North Island, is the largest natural harbour in the Southern hemisphere, covering an area of 947 km^2 at high tide and 538 km^2 at low tide (Heath, 1976). Tidal flows of up to 2.4 m s^{-1} are sometimes recorded during spring tides, making them the largest tidal flows in New Zealand, though characteristic peak channel tidal flows are around 1.8 m s^{-1} (Hicks & Hume, 1996; Bellvé*, et al.*, 2007; Vennell, 2011).

In 2006, Crest Energy Limited submitted its first proposal for a tidal energy project in the Kaipara Harbour. As well as contributing to a reduction in greenhouse gas emissions, the project aimed to alleviate some of the strain on the current electricity supply to northern Auckland and Northland (Bellvé*, et al.*, 2007). The application for the development of a tidal turbine power station in the Kaipara Harbour by Crest Energy, Ltd was approved by New Zealand's Minister of Conservation in March 2011 after much opposition from various stakeholders. In 2013, however, the project was indefinitely put on hold. Despite this, many of the specifications proposed in the Kaipara Marine Turbine Generation Project are considered representative of similar projects, and are thus used as a baseline in this thesis.

The Kaipara Marine Turbine Generation Project proposed to place tidal turbines in the entrance channel of the Kaipara Harbour (see Figure 1.1), where tidal flows are the highest. The tidal array would consist of up to 200 turbines arranged in clusters over an area of about 18 km^2 of the harbour entrance channel. Up to 30 turbines would make up a cluster, and would be connected as a series array – rather than individually – through a direct current (DC) ringmain cable to a centralised 'junction box.' The 10km of

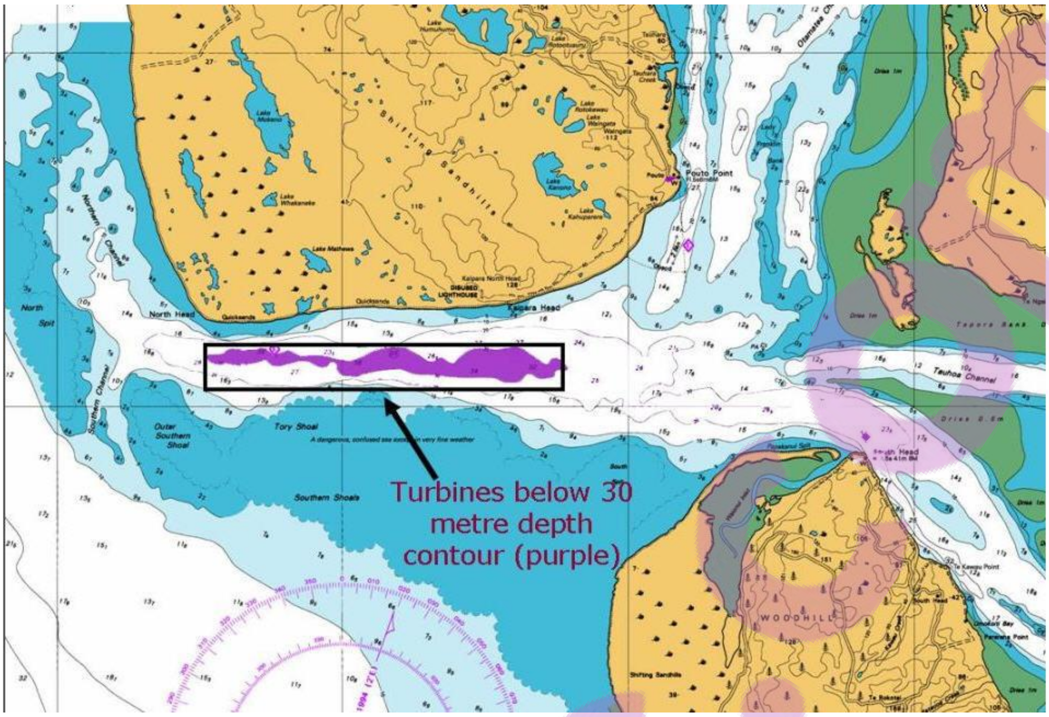


Figure 1.1 – Map of the entrance to the Kaipara Harbour. The shaded purple area shows the proposed location for installation of the tidal turbines for the Kaipara Marine Turbine Generation Project. (From Crest Energy Ltd, http://www.crest-energy.com/images/large/q005.jpg)

ringmain cables for each cluster would lie directly on the seabed, anchored down by concrete ballast blocks (CEL, 2006; Bellvé*, et al.*, 2007).

Two single high voltage DC (HVDC) bipole cables would link the 'junction box' to an onshore substation, where the electricity would be converted to AC and connected to the national transmission grid. The two HVDC cables would be entrenched in the seabed at a depth of around 1m (CEL, 2006; Bellvé*, et al.*, 2007).

1.3.2 Elasmobranchs in the Kaipara Harbour

During the consent process for the Kaipara Marine Turbine Generation Project, elasmobranchs were identified as being of potential concern. A number of elasmobranch species are found in the Kaipara Harbour, ranging from benthic shark and ray species to species such as great white sharks (*Carcharodon carcharias* Linnaeus, 1758). It is thought to be particularly important as a secondary nursery habitat for smooth hammerheads (*Sphyrna* *zygaena* Linnaeus, 1758), and known to be an important primary nursery habitat for rig (*Mustelus lenticulatus* Phillipps, 1932), with pregnant females migrating there in Spring (Duffy, 2011). It is likely to act as an important nursery habitat for other elasmobranch species, too.

For other elasmobranch species, the Kaipara Harbour represents seasonal feeding grounds (Duffy, 2011). As the elasmobranchs that make seasonal use of the harbour migrate in and out of the harbour mouth, benthic species in particular are likely to encounter the submarine power cables proposed as part of the Kaipara Marine Turbine Generation Project. Given elasmobranchs' extremely sensitive electrosensory system, it is currently unclear whether the EMFs associated with such cables, which are within the range detectable by elasmobranchs, could affect and potentially alter their behaviour, possibly leading to concerning impacts (Normandeau, *et al.*, 2011).

1.4 The elasmobranch electrosensory system

Electroreception is considered an ancestral characteristic of vertebrates, but has only been retained by four orders of teleosts, most non-teleost fish, including elasmobranchs, with a few additional examples, such as the platypus (*Ornithorhynchus anatinus* Shaw, 1799) and other monotreme mammals. Contrary to electric organs such as those found in electric catfish and electric rays, which enable the animal to actively produce an electrical discharge and are thought to have later evolved in several taxa at least six separate times, electroreception is a passive sense, and generally used for detection of prey, predators and conspecifics (Bodznick & Boord, 1986; Zupanc & Bullock, 2005).

The morphology and sensitivity of the elasmobranch electroreceptive system varies across species, and reflects the vast interspecific variation in habitat, prey and foraging strategies amongst elasmobranchs (Raschi, 1978; Tricas, 2001). Experiments with dusky smooth-hounds (*Mustelus canis* Mitchell, 1815) have demonstrated sensitivity to electric potentials as weak as

5 nV cm^{-1} (Kalmijn, 1982). It is worth noting that whilst nV cm^{-1} is not a standard SI unit, it is used in this thesis to facilitate the comparison between the weak electric fields induced by power cables and the extreme sensitivity of elasmobranchs, and is typically used in the field of elasmobranch electrosensitivity. Juvenile scalloped hammerheads (*Sphyrna lewini* Griffith & Smith, 1834) and sandbar sharks (*Carcharhinus plumbeus* Nardo, 1827) demonstrated behavioural responses to thresholds as low as 1 nV cm^{-1}, as have neonatal bonnethead sharks (*Sphyrna tiburo* Linnaeus, 1758) (Kajiura & Holland, 2002; Kajiura, 2003). Some authors have suggested that the head movements of the sharks during experiments increased the electric potential and thus the detection threshold isn't actually as low as reported and may be closer to 20 nV cm^{-1}, which is still a very weak electric field and nonetheless demonstrates the extreme sensitivity of the elasmobranch electrosensory system (Petracchi & Cercignani, 1998).

1.4.1 Mechanisms of electroreception

The sensory receptors in the elasmobranch electroreceptive system, known as the ampullae of Lorenzini, are classified as ampullary receptors (Zupanc & Bullock, 2005). Each ampulla consists of several alveolar bulbs clustered around the base of a single canal (see Figure 1.2A). The epithelium of each alveolus is lined with sensory receptors and support cells, which respond to differences between the electric potential of an internal reference potential and the potential of an external stimulus. Each canal leads from the subdermal ampulla to a small dermal electrosensory pore, and is filled with a low-resistivity mucopolysaccharide gel so the electric potential that reaches the electroreceptor is similar to the potential at the pore (Waltman, 1966; Bodznick & Boord, 1986; Sisneros & Tricas, 2002; Tricas & Sisneros, 2004; Gardiner, *et al.*, 2012).

Individual ampullae of Lorenzini are grouped together into clusters from which the canals radiate towards the pores, with between three and six clusters per side of an animal, depending on the species (Gardiner, *et al.*, 2012).

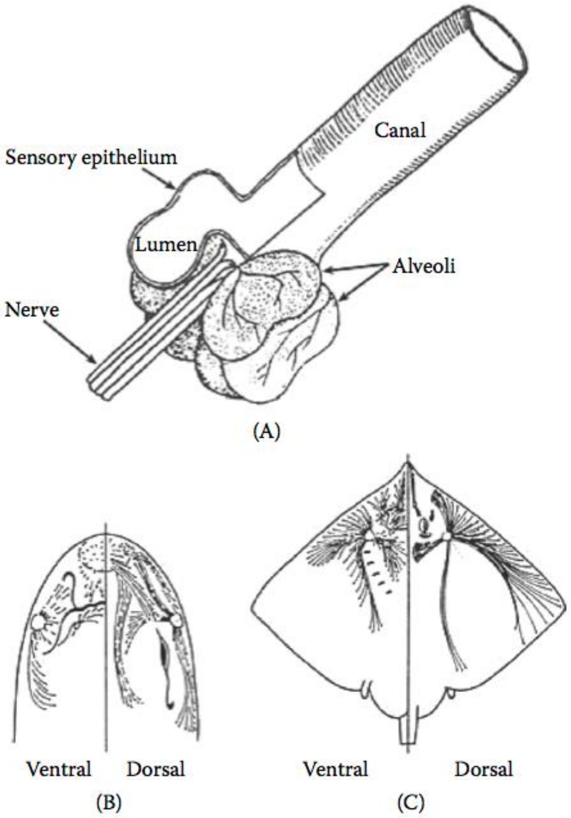


Figure 1.2 – Elasmobranch ampullary electroreceptive organs. (A) Representation of a subdermal ampulla of Lorenzini which consists of several alveolar bulbs clustered around the base of a single canal which leads to the dermal electrosensory pore. (B) Representation of the canal radiation from the cluster of ampullae in the lesser spotted dogfish (*Scyliorhinus canicula* Linnaeus, 1758) showing the concentration of pores around the head and mouth and (C) in the thornback ray (*Raja clavata* Linnaeus, 1758) showing the radiation around the head, mouth and periphery of the wings (from Gardiner*, et al.*, 2012).

The location of the electrosensory pores has been linked to the habitat and prey of different species. As demonstrated in Figures 1.2B and 1.2C, in sharks, the pores are generally clustered around the head and mouth, whereas in rays, the canals tend to radiate in all directions from the ampullary clusters and pores are found around the head and mouth but also around the periphery of the wings (Zakon, 1986; Tricas & Sisneros, 2004; Gardiner*, et al.*, 2012; Kempster*, et al.*, 2012; Bedore*, et al.*, 2014). Canal length has been positively correlated to ampullary sensitivity (Bodznick & Boord, 1986; Tricas & New, 1998).

Sensory information is conveyed to the central nervous system by the primary afferent neurons of the anterior lateral line nerve which innervate the ampullae of Lorenzini. Information travels to the dorsal octavolateralis nucleus (DON) in the medulla of the elasmobranch hindbrain. Electrical fields or "noise" produced by an individual which could confound the signals from potential prey are filtered out by the DON such that only non-confounding signals continue through ascending efferent neurons to the mesencephalon of the midbrain (Bodznick & Boord, 1986; Montgomery & Bodznick, 1993; Bodznick*, et al.*, 1999; Gardiner*, et al.*, 2012).

1.4.2 Detection of prey

Marine organisms produce weak bi-polar electric fields as part of the process of osmoregulatory ion exchange with seawater. In teleosts, this occurs particularly around the epithelial tissues of the mouth and gills. Electrical signals are also produced through the direct movement of muscles or firing of nerves (Potts & Hedges, 1991; Wilkens & Hofmann, 2005; Kimber*, et al.*, 2011).

The capacity for the elasmobranch electroreceptive system to detect very weak, low frequency bioelectric fields enables its use in the detection of the bioelectric fields produced by prey. The first demonstration of this was with lesser spotted dogfish (*Scyliorhinus canicula* Linnaeus, 1758) and thornback rays (*Raja clavata* Linnaeus, 1758) which showed directed feeding responses to buried flounder and flounder buried in an agar chamber which allowed the flounder's bioelectric fields to pass through but shielded any olfactory stimuli. When the flounder's bioelectric fields were also shielded, the elasmobranchs did not show any feeding responses. Dipole electrodes simulating similar fields to the flounder and hidden in the sand or in an agar chamber also elicited feeding responses from the elasmobranchs (Kalmijn, 1971).

Field experiments have been conducted with *Mustelus canis* and blue sharks (*Pionace glauca* Linnaeus, 1758) where the sharks were attracted to the experimental set-up using an olfactory stimulus. However, when given a choice between the source of the olfactory stimulus and dipole electrodes simulating electric field similar to prey, the sharks attacked the electrodes (Kalmijn, 1982). Whilst odour stimuli can be carried a long distance and allow the initial detection and tracking of prey, electroreception clearly plays a key part in the accurate near-field location of prey, even amongst species that do not necessarily feed on buried prey (Wilkens & Hofmann, 2005; Gardiner, *et al.*, 2012).

1.4.3 Detection of conspecifics

Round stingrays (*Urolophus halleri* Cooper 1863) have been shown to use electroreception to detect the bioelectric fields partially produced through the ventilator movements of the gill slits and spiracles of conspecifics during the mating season. Males use electroreception to detect buried females to mate with. Females use electroreception to locate other buried females, possibly to find refuge for less receptive females (Tricas, *et al.*, 1995; Sisneros & Tricas, 2002). Other benthic species that often bury into the sediment may show similar behavioural use of electroreception.

1.4.4 Detection of predators

Elasmobranchs have also been shown to use electroreception in the detection of predators. Embryos of both the oviparous clearnose skate (*Raja eglanteria* Bosc, 1800) and brown-banded bamboo shark (*Chiloscyllium punctatum* Müller & Henle, 1838) have been shown to react to electrical fields corresponding to natural signals produced by their potential predators. Whilst still in their egg cases, the embryos cannot physically escape or hide, so they responded to the signals by pausing gill movements and coiling the tail around the body, thus minimising any electrosensory and/or mechanosensory signals that could be detected and pinpointed by a nearby predator (Sisneros, *et al.*, 1998; Kempster, *et al.*, 2013).

1.4.5 Detection of geomagnetic fields

Seawater's electrolytic properties mean that motional electric fields are induced as it flows through the Earth's magnetic field, a phenomenon which was first noted by Michael Faraday in 1832 (von Arx, 1962; Manoj*, et al.*, 2006). Based on circumstantial evidence, and backed up by a number of experiments, it is generally accepted that elasmobranchs use such fields to navigate the oceans on a large, possibly global, scale (Klimley, 1993; Klimley*, et al.*, 2002; Meyer*, et al.*, 2005). Whilst it has been shown that sharks can detect changes in geomagnetic fields, it is not yet clear whether the mechanism of detection of these fields stems from induction-based electroreception or direct magnetoreception through magnetite-based receptors (Montgomery & Walker, 2001; Meyer*, et al.*, 2005; Molteno & Kennedy, 2009).

Experiments involving magnets placed in the nasal cavity of a short-tailed stingray (*Dasyatis brevicaudata* Hutton, 1875) resulted in impaired discrimination of magnetic stimuli and appeared to confirm direct magnetoreception (Kirschvink*, et al.*, 2001). However, such a conclusion would require less than 100μm of relative movement between the magnets and the electroreceptive system, a criterion that is unlikely to have been met. Consequently, it is difficult to elucidate whether elasmobranchs are directly magnetoreceptive or rely indirectly on their electrosense to navigate (or a combination of both), and the matter is still under fervent debate (Molteno & Kennedy, 2009; Kirschvink*, et al.*, 2010).

1.4.6 Electricity-based elasmobranch deterrents

There is well-documented evidence of elasmobranchs avoiding strong, artificial magnetic fields (O'Connell*, et al.*, 2010, 2011). There is also evidence of elasmobranchs avoiding very large electrical voltage potentials. Strong magnetic and electrical fields are thought to irritate and potentially overwhelm the elasmobranchs' electroreceptive system, although the upper parameters of the electrosensory system have yet to be determined (Howard, 2011).

It has been suggested that elasmobranch bycatch could be reduced with electricity-based deterrent devices that would irritate and deter elasmobranchs but not target teleost species. As yet, there has been little success in the development of commercially-viable bycatch reduction devices due to various practical considerations and problems with habituation (Stoner & Kaimmer, 2008; Howard, 2011). Electricity-based shark repellent devices for divers have been developed, and although few have been rigorously tested, the Shark Shield Freedom7™ has been shown to be effective at deterring great white sharks, despite some apparent habituation (Kempster*, et al.*, 2016a).

There have also been instances where intended deterrents have instead acted as attractants, suggesting that elasmobranchs' responses to strong magnetic or electric fields are context-dependent and extremely variable between species (Huveneers*, et al.*, 2013; O'Connell*, et al.*, 2014a; Porsmoguer*, et al.*, 2015).

1.5 Elasmobranchs and power cables

When given a choice between artificial and natural DC electrical fields of similar magnitudes, *Scyliorhinus canicula* does not show a preference between the two. It is not clear whether this is because the dogfish cannot differentiate between the two or whether they can, but do not have a preference in the absence of other sensory information such as visual and olfactory cues (Kimber*, et al.*, 2011). Regardless, these findings have implications with regards to anthropogenic electric fields in the marine environment, such as those around power cables.

Submarine power cables such as the DC ringmain cables in the proposed Kaipara Marine Turbine Generation Project have magnetic fields around them. Since the generation of energy by the turbines depends entirely on tidal flows, it is inevitable that there will be seawater flowing through those magnetic fields, and secondary electrical fields will be induced, as detailed in Chapter Two. If these induced electrical fields are within the electroreceptive spectra of elasmobranchs, then they could have behavioural impacts. The strength of the field at any given point will depend on the electrical current through the cable, the distance from the cable (regardless of whether it is buried or not) and the velocity of the seawater flow. In the case of a buried cable, the magnetic field will be present within the substrate, but unless there is seawater flow between the particles of sediment, a secondary electric field will not be induced within the substrate.

If the induced electrical fields are at the higher end of the electroreceptive spectrum, a deterrent effect could be observed. Whilst the area of impact will be restricted to a corridor along or across the cable, migration routes travelling over the cables could be disrupted if an avoidance response is caused (Wilson*, et al.*, 2010; Normandeau*, et al.*, 2011).

Conversely, if the induced electrical fields are in a similar range to those of a species' prey, the cables may elicit an attraction and foraging response (Wilson*, et al.*, 2010; Kimber*, et al.*, 2011). Many electroreception experiments involve the use of artificial fields that approximate those of prey and to which elasmobranchs generally show a foraging response (Kalmijn & Weinger, 1981; Kalmijn, 1982; Gardiner*, et al.*, 2012). This could lead to poor foraging success within the vicinity of cables, particularly in benthic species that forage for buried prey and are particularly reliant on their electrosensory system. This may eventually have implications on population fitness if an area is used as a nursery ground, for example (Wilson*, et al.*, 2010; Kimber*, et al.*, 2011).

It is possible that any negative behavioural effects of underwater cables would diminish over time as animals either habituate or learn to avoid an area of poor foraging success. However, this is only likely to be the case in populations that are relatively sedentary. Migratory populations or species may be more heavily impacted (Guttridge*, et al.*, 2009).

1.5.1 Current research into submarine power cable impacts

Research into the effects of submarine power cables on elasmobranchs is currently very limited (Boehlert & Gill, 2010; Kimber*, et al.*, 2011; Normandeau*, et al.*, 2011; Gill*, et al.*, 2014). A number of literature reviews and reports on the theoretical effects of anthropogenic EMFs on elasmobranchs have been published, and, whilst an important starting point to consider and explore potential impacts, these do not provide the concrete evidence required to accurately conduct environmental impact assessments (EIAs) and put appropriate environmental regulations into place (Boehlert & Gill, 2010; Normandeau*, et al.*, 2011; Gill*, et al.*, 2014).

One of the few dedicated studies that have been conducted so far, the Collaborative Offshore Wind Research into the Environment (COWRIE) mesocosm study, monitored the behaviours and movements of elasmobranchs in relation to submarine power cables in the field. This was done through tracking the movements of several individuals of different species – thornback rays, spiny dogfish (*Squalus acanthias* Linnaeus, 1758) and lesser spotted dogfish – in large enclosures set over power cables. Both inter- and intra-specific variation in responses were found, but it was concluded that whilst further research was necessary, it was clear that certain individuals were definitely detecting and responding to the active cables, mostly by moving closer to them, suggesting attraction, perhaps through foraging (Gill*, et al.*, 2009, 2014).

The COWRIE study clearly demonstrates that further research is imperative. This thesis approaches the question of potential impacts from a laboratory-based perspective in order to better understand behavioural responses of elasmobranchs to EMFs around submarine power cables when all other factors are controlled. Running initial experiments in a laboratory setting will serve as a solid basis for necessary future field studies, where more factors will be involved and it may be more difficult to tease out the extent of EMF impacts versus other environmental factors, such as prey distribution in the sediment, or complex seawater currents and eddies (Gill*, et al.*, 2009; Normandeau*, et al.*, 2011).

The cable specifications chosen for investigation in this thesis are considered representative of those found internationally, though it is important to note that conditions such as seawater flow and direction are variable between sites, so EMF strengths will be variable, too. As a result, elasmobranch responses towards the EMFs around submarine power cables at different locations are likely to differ. The responses observed in this study provide a starting indication of the impacts of EMFs around submarine power cables, but a significant amount of further investigation will be required to draw definitive conclusions that cover all submarine power cables and all elasmobranch species.

1.5.2 Elasmobranchs and fibre optic cables

Whilst there is a current dearth of research on the impacts of submarine power cables, elasmobranchs are known to occasionally bite fibre optic cables. Not a great deal of research has been conducted on this either, but based on bite marks and teeth left in the cable insulation, a range of species are responsible. Interestingly, not all identified species were benthic, leading to suggestions that the cables were bitten during deployment or recovery, or on deep-water sections that were not flush with the seabed (Marra, 1989; Bres, 1993). The induced electric fields surrounding one of the first recorded fibre optic cables to be bitten were evaluated at 630 μV cm^{-1} by Marra (1989) which is several orders of magnitude higher than the EMFs calculated for the cables investigated in this thesis. The sharks are likely to have been attracted by the EMFs, or, if the cable's insulation layer was damaged, by weak galvanic fields created by contact between exposed metal and seawater.

Whilst beyond the remit of this thesis, which specifically concentrates on the impacts of submarine power cables, it is important to remember that, as evidenced above, many other types of cables also cross the oceans, and may have differing impacts. However, investigating the effects of submarine power cables may also elucidate some of the effects of other cables which may share similar characteristics, notably the induction of weak EMFs around them in seawater.

1.6 Working with elasmobranchs in a laboratory setting

Whilst the necessity of running initial laboratory experiments is clear, there are a number of considerations when running laboratory experiments on elasmobranchs. Not all elasmobranch species are suitable for captivity – evidently, the larger a species, the harder it is to accommodate it comfortably. The same is true for more pelagic species, which, as a rule, require a huge amount of unrestricted space for swimming, mirroring their natural habitat (Dehart, 2004; Powell*, et al.*, 2004). Since benthic species are by far the most likely to encounter submarine power cables laid on the seabed, benthic species are evidently most appropriate to use as study species in this particular thesis. Conveniently, benthic species are generally also more manageable in a laboratory setting due to their small space requirements.

In terms of the amount of space required to house study animals, other important considerations include whether a species is territorial and individuals each need their own tank and whether sexes must be separated, which usually depends on whether any males are sexually mature or not.

A number of other factors also contribute to choosing an appropriate laboratory species, including how quickly the animals adapt to new tank environments, how hardy they are in terms of being handled or moved into and out of the experimental tank, and how much stress they show in a captive environment. Another very important consideration is how easy it is to obtain the number of individuals required, and following on from that, if catching the species from the wild, how damaging the method of capture is to the animals. The New Zealand carpet sharks (*Cephaloscyllium isabellum* Bonnaterre, 1788) used in Chapters Four and Five were caught as bycatch in the cray pots of local commercial fishermen. This was a preferred source of sharks since the animals didn't sustain any hook or other injuries, which made them far less susceptible to possible infection in the tanks.

1.7 Objectives and structure of this thesis

The main objective of this thesis is to begin to understand the behavioural effects that EMFs associated with submarine power cables have on benthic elasmobranchs, and whether those effects are likely to translate into impacts. Whilst there have been calls for research in this area, few studies have been conducted. This thesis therefore aims to start addressing this paucity of data, and act as a foundation to indicate direction for further studies.

Chapter Two describes the physics behind the generation of EMFs around both alternating current (AC) and direct current (DC) submarine power cables, including how to calculate expected strengths.

Chapter Three kick-starts the investigation into the effects of submarine power cables through a series of pilot experiments using New Zealand eagle rays (*Myliobatis tenuicaudatus* Hector, 1877) and low-power DC cables.

Chapter Four refines the experimental design used in Chapter Three to investigate the behavioural effects of submarine AC power cables through a series of experiments with New Zealand carpet sharks. Based on the results, conclusions are drawn regarding the likelihood of impacts of submarine AC power cables.

Chapter Five investigates the behavioural effects of submarine DC power cables, also using New Zealand carpet sharks. Subsequent to the findings on behavioural effects, the sharks' habituation towards the EMFs around the power cables is investigated. Based on the results of both, conclusions regarding the likelihood of impacts of submarine DC power cables are discussed.

Chapter Six integrates the findings from the three preceding data chapters and discusses them as a whole, drawing overall conclusions on the likely impacts of EMFs associated with submarine power cables, and suggesting directions for future research to broaden the understanding gained in this thesis.

CHAPTER TWO:

THE GENERATION OF ELECTROMAGNETIC FIELDS AROUND SUBMARINE POWER CABLES

2.1 Introductory overview

Power cables are required to transfer electricity from the source of generation to wherever it is required. Submarine power cables are used to transfer electricity across water bodies, and this use will increase with the advent of off-shore generation by wind-farms, wave and tidal power. In conditions where seawater flows over the cables, weak electromagnetic fields are generated, which may fall within the detection range of the elasmobranch electrosensory system giving rise to concerns that submarine cables may adversely affect their behaviour and movements. The cable specifications are chosen based on a number of factors, including the distance of transmission and transmission efficiencies. The nature of the fields generated and their strengths and geometry are in turn determined by the cable specifications, cable layout and the movement of seawater over the cables. This chapter sets out the common cable specifications and the implication this has for induced electrical fields, the physics as to how the fields are generated around submarine cables and details a worked example based on the Kaipara Marine Turbine Generation Project tidal turbine proposal.

2.2 Electricity generation and transmission

Electricity generated by transforming kinetic energy into electrical energy is a process which makes use of Faraday's Law of Induction. This law is a statement of the electromotive force (emf) that will result from a conductor interacting with a magnetic field. This can occur through a change in the positions of the magnet and the coil relative to each other, and in electricity generation this is generally achieved by rotating the coil of wire relative to the magnet (Sears & Zemansky, 1964; Herman, 2012; Radi & Rasmussen, 2013).

In practice, a turbine of some sort is used to drive the rotation of the coil of wire. Traditionally, steam-driven turbines were used, with the steam generated through the burning of fossil fuels such as coal and gas (Laughton & Warne, 2003). However, given the association between the burning of fossil fuels and environmental degradation, there is rapidly increasing interest in using alternative "renewable" or "green" energy, sourced both onshore and offshore, to drive turbines (Laughton & Warne, 2003; Gill, 2005). Geothermal energy can be directly harnessed for steam-driven turbines, but other sources of energy used to drive turbines mainly rely on harnessing the kinetic energy of water or wind to drive turbines, for example through dams or tidal turbines, and wind turbines, respectively (Laughton & Warne, 2003).

Regardless of the source of energy used to generate the electricity, it then needs to be transported from the source of generation to where it is actually needed, using power cables. When these power cables are surrounded by a moving electrically-conductive medium, such as seawater, then Faraday's law again comes into effect and environmental electromagnetic fields are induced. The precise nature of these fields depends on the details of the transmission system, including the use of alternating current (AC) or direct current (DC), but the induced electric fields around many of these submarine power cables fall within the extremely sensitive electrosensory detection range of elasmobranchs.

2.2.1 Alternating current

AC is characterised by an alternating polarity at a specific frequency, or cycles per second, measured in Hertz (Hz). Electricity is generated in AC form in many power plants, because the strength of the current and its polarity in the rotating wire reflects the changing polarity of the magnetic field as the coil rotates through it (Laughton & Warne, 2003; Radi & Rasmussen, 2013).

Mains electricity is generally delivered as AC. In New Zealand and most other countries, mains electricity is delivered to houses at 50 Hz, but in certain countries, such as the USA, the standard is 60 Hz (Laughton & Warne, 2003).

2.2.2 Direct current

DC maintains a constant polarity and always flows solely in a single direction, from positive to negative (Radi & Rasmussen, 2013). Whilst power is delivered to houses in AC, most electronic devices require DC, and so have small rectifiers to convert the current, usually located within the plug housing (Herman, 2012).

2.2.3 Choosing cable specifications (alternating current *vs* direct current)

The lack of continuously changing current in DC cables mean that a DC cable core can generally transfer a larger amount of power than an AC cable core of an equivalent rating. Consequently, for long-distance uninterrupted power transmission, DC is much more efficient than AC (CEL, 2006; Bellvé*, et al.*, 2007; Herman, 2012). It is possible to convert electricity from AC to DC using a rectifier, and from DC to AC using an inverter, which is more complex than a rectifier. Since electricity is usually both generated and delivered to houses in AC, special rectifiers and inverters are required at each end to enable more efficient DC power transmission between these two points. However, since the converter stations required to house the rectifiers and inverters are expensive to build, DC power transmission is not necessarily more cost effective over short distances. The minimum distance over which DC becomes economically preferable varies with cable specifications (Bellvé*, et al.*, 2007; Herman, 2012).

Major losses in electrical circuits are proportional to the square of the current, thus cables that can transfer the same amount of power but at a higher voltage and therefore lower current, will incur fewer transmission losses. It is possible to step the voltage up and down by using transformers (Laughton &

Warne, 2003; Radi & Rasmussen, 2013). Consequently, there has been a move towards the use of high voltage DC (HVDC) cables as they allow notably more efficient electricity transfer over long distances than standard DC cables (Valenza & Cipollini, 1995; Chow, *et al.*, 2003). In the case of AC power transmission, there has been some recent investigation into high voltage low frequency AC (LFAC) power transmission, which offers improved transmission efficiency compared to standard high voltage AC (HVAC) cables but requires additional costly equipment to produce the appropriate low frequency (Manohara & Sonia, 2014).

2.3 Submarine power cables

Submarine power cables play an important role in the transport of electricity. The geographical distribution of power generation plants and resources does not necessarily match that of the population or demand for electricity. In New Zealand, the HVDC Inter-Island Link includes three HVDC submarine cables that transfer electricity between the two main islands. The link includes 40 km of submarine cables to transfer the electricity across the Cook Straight (Transpower, 2014). The Kaipara Harbour Marine Turbine Generation Project (refer to Chapter One) proposes the use of DC cables to link groups of turbines together and to a central ‘junction box’ and around 29 km of HVDC cables to transfer electricity from the central ‘junction box’ to shore (CEL, 2006).

Globally, there are numerous submarine power cables that transmit power out to major islands or between countries, for example the Spain-Morocco Interconnection which runs two submarine HVAC cables for 26 km across the Mediterranean, or the Basslink between mainland Australia and Tasmania which includes 290 km of HVDC submarine cables that run across the Bass Straight (Valenza & Cipollini, 1995; Basslink, 2012). Submarine cables are also used to transfer electricity across estuaries or to near-shore islands over shorter distances than the examples mentioned above.

With the advent of offshore power generation, a particular growth area of submarine cables is the transmission of energy from renewable sources such as wind turbine farms or tidal turbine networks to where it is required and can be fed into the national grid (Pimentel, *et al.*, 2002).

2.3.1 Electromagnetic fields around direct current submarine power cables

An electrical current flowing through a DC power cable generates a very weak magnetic field around the cable, perpendicular to the direction of the electrical current, resulting in a circular magnetic field around the cable (Sears & Zemansky, 1964). This magnetic field is not impeded by the cable's plastic insulation jacket, which only insulates the surrounding environment from the electrical current within the cable and also provides structural protection (York, 2010). If the electrical current is DC, the direction of electrical current remains constant and the magnetic field is sustained. The strength of this magnetic field is dependent on the magnitude of the electrical current passing through the cable and quickly attenuates with distance from the cable (Sears & Zemansky, 1964; Wilson, *et al.*, 2010). The strength of the magnetic field can be calculated as follows (Equation 2.1, from Sears & Zemansky (1964)):

$$B = \frac{\mu_0 \, I}{2\pi r} = \frac{4\pi \times 10^{-7} \times I}{2\pi r} = \frac{2I \times 10^{-7}}{r} \qquad \textbf{(Equation 2.1)}$$

Where B *= magnetic flux density (teslas, T)*

μ_0 = magnetic permeability (for seawater, taken as $4\pi \times 10^{-7}$ henries per metre, $H\ m^{-1}$)

I = current through cable (amperes, A)

r = distance from cable (metres, m)

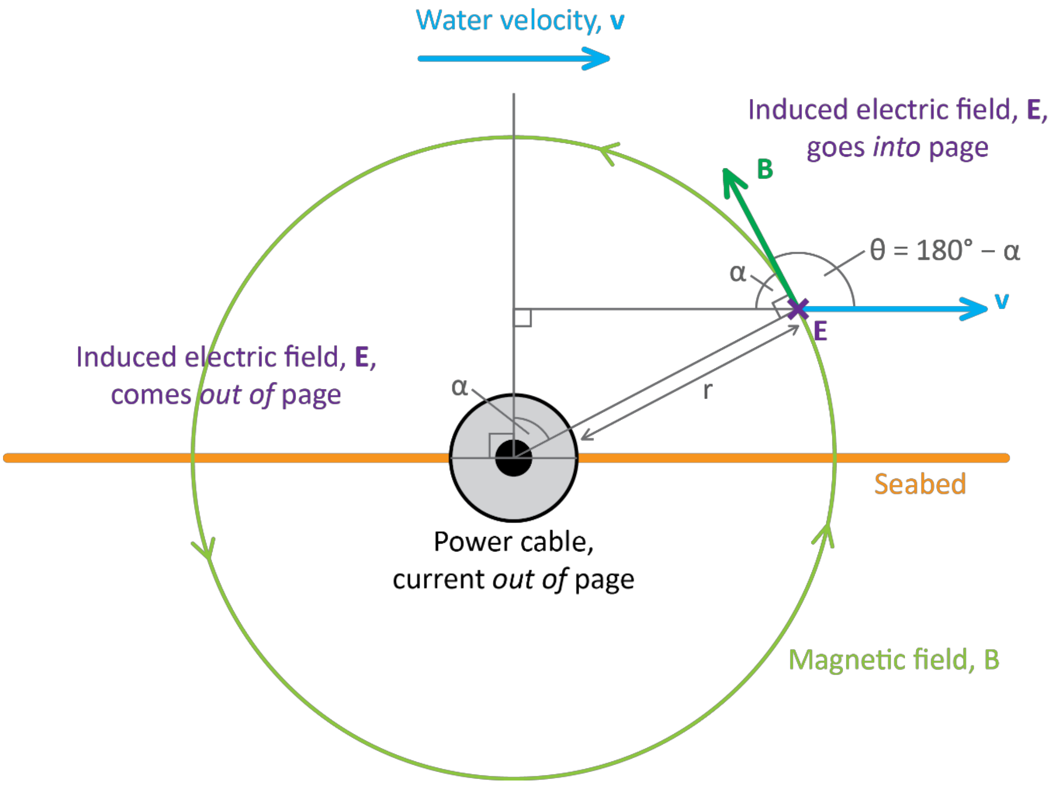


Figure 2.1 – Diagrammatic representation of the EMFs around a cable, illustrating the vectors used for calculations. The smallest angle between vectors **v** and **B**, θ, must be determined in order to calculate the magnitude of E, the induced electric field strength, using Equation 2.3. This can be done using basic trigonometry. After Sears & Zemansky (1964).

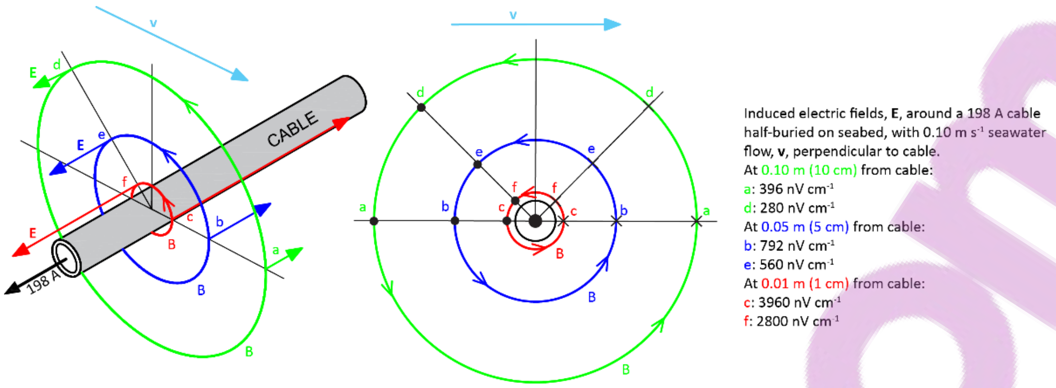
In the case of submarine power cables, electrically-conductive sea water flows through this very weak magnetic field which, in turn, generates a very weak induced electrical field, as shown in Figure 2.1. This follows the same principle as Faraday's Law of Induction, with an electrically-conductive medium – the sea water – moving through a magnetic field – around the cable (von Arx, 1962; Sears & Zemansky, 1964; Öhman*, et al.*, 2007; York, 2010). The strength of the induced electric field can be calculated with the following vector equation (Equation 2.2, adapted from Sears & Zemansky (1964) and York (2010)):

$$\boldsymbol{E} = \boldsymbol{v} \times \boldsymbol{B} \qquad \textbf{(Equation 2.2)}$$

*Where **E** = induced electric field vector (volts per metre, V m^{-1})*

***v** = seawater velocity vector (meters per second, m s^{-1})*

***B** = magnetic intensity vector (T)*



Induced electric fields, **E**, around a 198 A cable half-buried on seabed, with 0.10 m s^{-1} seawater flow, **v**, perpendicular to cable.
At 0.10 m (10 cm) from cable:
a: 396 nV cm^{-1}
d: 280 nV cm^{-1}
At 0.05 m (5 cm) from cable:
b: 792 nV cm^{-1}
e: 560 nV cm^{-1}
At 0.01 m (1 cm) from cable:
c: 3960 nV cm^{-1}
f: 2800 nV cm^{-1}

Figure 2.2 – Diagrammatic representation of the EMFs around a 198 A submarine power cable, with examples of induced electric field strengths, **E**. The green, dark blue and red arrows are vectors and show the relative magnitudes of the induced electric fields at different distances from the cable at a seawater flow, **v**, of 0.10 m s^{-1} perpendicular to the cable. The electrical current and seawater flow parameters in this diagram are those used in the experiments in Chapter Five. Please refer to Section 2.4 to see an example calculation of field strengths.

Thus, it follows that (Equation 2.3):

$$E = v\ B\ sin\theta \qquad \textbf{(Equation 2.3)}$$

Where E = induced electric field strength (V m^{-1}*)*

v = seawater velocity (m s^{-1}*)*

B = magnetic field strength (calculated in Eq. 2.1, T)

θ = smallest angle between ***v*** *and* ***B*** *(see Fig. 2.1)*

The strength of the weak induced electric field depends on the magnetic field strength, the velocity of the sea water flowing through the magnetic field, and the angle at which sea water is flowing through the field, resulting in varying field strengths around the cables, as shown in Figure 2.2. Since the electric field strengths relevant to elasmobranchs are usually so weak, they are often presented in nV cm^{-1} or µV cm^{-1} for ease of use.

Since both the magnetic and induced electric fields around the cable attenuate relatively quickly with distance, the most obvious way to reduce any impacts from these fields would be to bury the cables far enough under the substrate that the magnetic fields reaching the substrate are considered negligible in terms of any potential impacts. This is not necessarily a viable option depending on, amongst other factors, the substrate material, topography and the maintenance needs of the cable (CEL, 2006).

2.3.2 Electromagnetic fields around alternating current submarine power cables

AC cables normally have two equal currents running in opposite directions, resulting in the generated magnetic fields described in the DC case nullifying each other. Consequently, in the ideal theoretical case, AC cables have no magnetic field external to the cable, and therefore no external induced electric field either (C. Tindle, pers. comm., 2015, University of Auckland).

However, in reality, the conductors within the cable will not be perfectly aligned, or an asymmetric rotation of the AC field through the cable may occur, and so the magnetic fields may not entirely cancel each other out, resulting in a very weak alternating magnetic fields around the power cable. As in the DC case, the presence of electrically-conductive seawater moving through these weak magnetic fields would result in very weak induced electric fields, potentially detectable by elasmobranchs (Normandeau, *et al.*, 2011). The geometry and strengths of these fields are difficult to model precisely, due to their alternating nature, but given the extreme sensitivity of the elasmobranch electrosensory system, experimentally testing elasmobranch behavioural responses to AC cables is warranted.

2.4 A worked example

As explained in Chapter One, the EMF strengths to be investigated are based on the proposed specifications of the Kaipara Marine Turbine Generation Project, in particular the DC cables that will connect the turbines to each other in a channel that has spring tides reaching up to 2.4 m s^{-1}, and will be rated to a maximum of 350 A. The cables will be laid directly on the seabed.

Using Equations 2.1, 2.2 and 2.3, the strength of the induced electric field at any given point around a DC submarine cable can be calculated. The specifications above are the extremes of both electrical current through the cables and seawater flow over the cables – of greater interest are the more typical seawater flows and electrical currents, as outlined in Chapter One. The values given in Figure 2.2 are based on such conditions, and the induced electric field strength 0.10 m from a 198 A DC cable sitting on the seabed with a seawater flow of 0.10 m s^{-1} perpendicular to the cable, at 45° off the seabed (so α would be 45°, refer to Figure 2.1) would be calculated as follows:

$$B = \frac{2I \times 10^{-7}}{r} = \frac{2 \times 198 \times 10^{-7}}{0.10} = \frac{3.96 \times 10^{-5}}{0.10}$$

(**Equation 2.4**)

$$\therefore B = 3.96 \times 10^{-4}\ \mathrm{T}$$

Referring to Figure 2.2, $\theta = 180° - \alpha$*. At 45° off the seabed, assuming the cable is half-buried,* $\alpha = 45°$*. So:*

$$\begin{aligned} E = v\, B\, sin\theta &= 0.10 \times 3.96 \times 10^{-4} \sin(180° - 45°) \\ &= 2.80 \times 10^{-5}\ \mathrm{V\ m^{-1}} \\ \therefore E &= 280\ \mathrm{nV\ cm^{-1}} \end{aligned}$$

(**Equation 2.5**)

This is, of course, a calculation of the theoretical ideal case, and relies on a number of assumptions, including that the seawater flows at a constant rate exactly perpendicular to the cable, that the electrical current has no fluctuations, that the power cables are perfectly straight, etc. In reality, the induced electric fields around a submarine power cable are expected to be weaker than those calculated for the ideal theoretical case, and this should be taken into account when designing experiments. However, even though the actual EMFs will be weaker than theoretically calculated, elasmobranchs have been shown to respond to fields as low as 5 nV cm^{-1}, which is several orders of magnitude lower than the calculated theoretical fields, and thus the EMFs in question may be of concern, and the behavioural impacts of submarine power cables necessitates investigation.

2.5 Electromagnetic fields through a tidal cycle

As previously discussed, the strengths of electric fields induced around submarine power cables, whether DC or AC, are a function of the velocity of the seawater flowing through the magnetic field around the cable. Furthermore, in the case of the Kaipara Marine Turbine Generation Project, the power generated by the turbines (and therefore the strength of the electrical current through the DC interconnection cables and, consequently, the magnetic fields around the cables) will vary over the course of a tidal cycle.

Figure 2.3 demonstrates the theoretical potential power generation through the course of a tidal cycle by a turbine placed in the mouth of the Kaipara Harbour, based on a number of simplifying assumptions for the purposes of demonstration. It is important to note that there is a minimum water current required for the turbines to rotate, which is not included in Figure 2.3 due to the variation across turbine designs and placement, so the

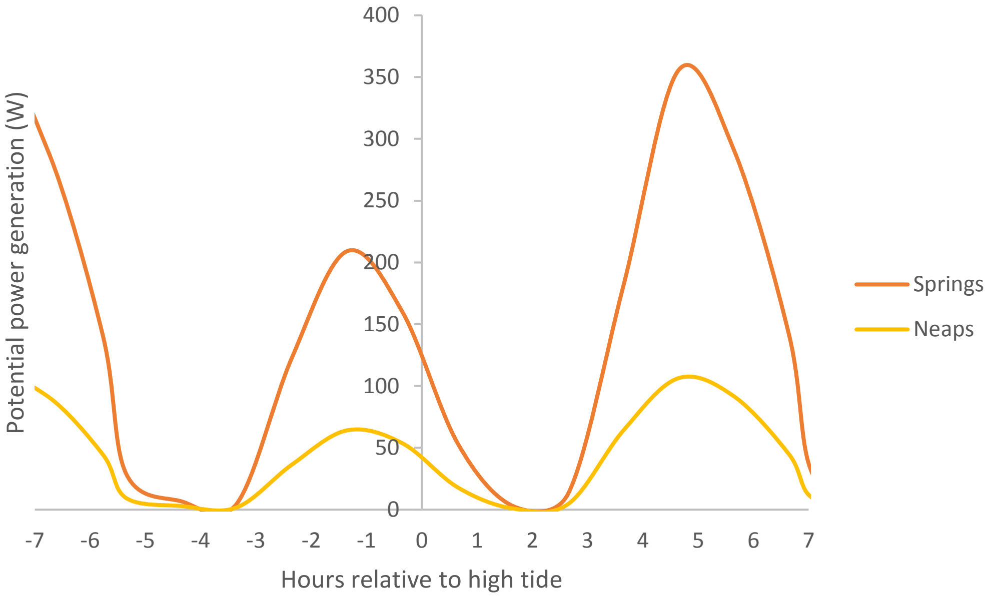


Figure 2.3 – Theoretical potential power generation by a turbine in the mouth of the Kaipara Harbour over the course of a tidal cycle, showing the clear dominance of ebb currents, a well-documented feature of the Kaipara Harbour. The turbine design proposed for the Kaipara Marine Turbine Generation Project optimises the tidal flow up to an angle of 40°, so the tidal stream angle has not been included and maximum turbine efficiency has also been assumed. Tidal steam information from LINZ (2008), power generation equation and turbine details from Bellvé*, et al.* (2007), power coefficient value from Ben Elghali*, et al.* (2007).

turbines will not generate power all the time. Consequently, there will not be a continual flow of electrical current through the interconnecting submarine power cables either, which means that weak electric fields induced around such submarine power cables will be both variable and not always present.

2.6 Summary

Submarine power cables are necessary for the transport of electricity, which can be in either AC or DC form. Following Faraday's Law of Induction, weak magnetic fields around the cables are generated by the passing of the current through the cable, and in turn, weak induced electric fields are generated by the flowing of electrically-conductive seawater through these magnetic fields. Whilst these weak EMFs attenuate quickly over distance, many of these fields at close-range to the cable are within the electrosensory detection range of elasmobranchs, and could consequently have behavioural impacts on these elasmobranchs.

CHAPTER THREE:

A PRELIMINARY INVESTIGATION INTO THE IMPACTS OF SUBMARINE POWER CABLES ON BENTHIC RAYS

3.1 Abstract

Electromagnetic fields (EMFs) are generated around submarine power cables. Although these EMFs are weak, they generally fall within the detection range of the elasmobranch electrosensory system and may interfere with foraging behaviours and movement. Ray species may be particularly vulnerable due to their benthic behaviour and high sensitivity. A preliminary investigation into the effects of DC power cables on New Zealand eagle rays (*Myliobatis tenuicaudatus* Hector, 1877) was investigated in the laboratory using a 30 A DC power cable in perpendicular 0.12 m s^{-1} seawater flow and no seawater flow. The electrical current was limited to 30 A by safety constraints. The rays crossed the active cable 51.8% of the time with flowing seawater, and 85.1% of the time with no seawater flow. They showed some avoidance behaviour towards the cable, but more commonly the rays investigated it. However, both response behaviours were shown towards both the active cable and the control hose, suggesting that these responses were triggered by visual or tactile cues. To clarify the potential impacts of power cables, further investigation is required where the confounding visual cue is removed and with higher electrical current in the power cable to better simulate submarine power cable specifications.

3.2 Introduction

3.2.1 Use of submarine power cables

Submarine power cables are required in order to transport electricity across bodies of water, for example, from offshore renewable energy developments (OREDs), or to near-shore islands. Such power cables can be either alternating current (AC), where the electrical current switches polarity at a specified frequency, or direct current (DC), where the electrical current remains constant. AC cables are generally used over shorter distances whereas DC cables are usually more cost-effective at distances over 40 km, but may also be preferable when bringing DC generated electricity to shore from OREDs.

Electrical current flowing through the submarine power cables generate magnetic fields around the cables. Electrically-conductive seawater flowing through these magnetic fields in turn induces weak electric fields that run parallel to the cables. Further details on the generation of these weak electromagnetic fields (EMFs) can be found in Chapter Two. Whilst the EMFs around submarine power cables are very weak, they generally still fall within the exceptionally sensitive detection range of the elasmobranch electrosensory system.

3.2.2 Electrosensory system of rays

Elasmobranchs have an extremely sensitive electrosensory system and dusky smooth-hounds (*Mustelus canis* Mitchell, 1815) have been shown to respond to fields as low as 5 nV cm^{-1} (Kalmijn, 1982). Due to the high accuracy of this sense over a short-range, the electrosensory system is important in the localisation of hidden prey, as well as conspecifics and in some cases, the detection of predators (Kalmijn, 1971, 1982; Tricas, *et al.*, 1995; Kempster, *et al.*, 2013). The importance of and reliance upon the electrosensory system varies across species, and is largely dependent on niche (Kajiura, *et al.*, 2010).

The location of electrosensory pores has also been linked to the habitat and prey of different elasmobranch species. Studies comparing electrosensory pore numbers and distribution between ray species have found inter-specific differences, predominantly linked to differences in foraging behaviours (Raschi, 1978; Jordan, 2008; Jordan, *et al.*, 2009a; Bedore, *et al.*, 2014). In general, as shown in Figure 1.2, sharks generally have clusters of pores around the head and mouth, whereas rays have pores that radiate around the periphery of the wings, as well as around the head and mouth (Zakon, 1986; Tricas & Sisneros, 2004; Gardiner, *et al.*, 2012). Consequently, rays often have longer electrosensory canals than similar-sized sharks, and the positive correlation between the length of canal and ampullary sensitivity suggests that in general, rays have more sensitive electrosensory systems than comparable shark species (Bodznick & Boord, 1986; Tricas & New, 1998).

Considering that the dorsally-located eyes of rays restricts their ability to see ventrally, the higher sensitivity of rays' electrosensory system and the distribution of electrosensory pores around the periphery of their wings is not surprising. Thus, benthic-feeding rays, such as the New Zealand eagle ray (*Myliobatis tenuicaudatus* Hector, 1877), are highly reliant on their electrosensory system in the detection and pin-pointing of prey buried in the sediment, and consequently likely to be impacted by the induced EMFs around submarine power cables (Tricas, 2001; Le Port, 2003). Benthic elasmobranchs are also significantly more likely to actually encounter submarine power cables and their associated EMFs, adding to the potential likelihood of impacts.

3.2.3 Expected impacts of submarine power cables on rays

The EMFs around many submarine power cables fall within the detection range of elasmobranchs, and consequently, there is concern that the EMFs may have a behavioural impact on benthic elasmobranch species that encounter them. Ray species may be particularly susceptible, given the even more specialised morphology of their electrosensory systems. Of notable concern is the potential for the EMFs to deter rays and prevent them from crossing cable zones, or to attract rays and act as phantom prey.

The use of electric fields or permanent magnets to deter elasmobranchs, particularly from fishing gear or humans in the water, has been studied with mixed results. In certain cases the magnets which were supposed to repel sharks were, in fact, found to attract them, and other studies observed rapid habituation to the initially-repulsive electric fields or magnets (Howard, 2011; O'Connell*, et al.*, 2011, 2014b; Porsmoguer*, et al.*, 2015). Since these systems aim to overwhelm the electrosensory system of elasmobranchs, the electric and magnetic fields used tend to be at the upper end of the electrosensory detection range, usually above 10 μV cm^{-1} (Howard, 2011; Kimber*, et al.*, 2011). The EMFs around submarine power cables are usually well below the upper end of the electrosensory detection range, and so are less likely to cause avoidance behaviours.

The EMFs may, however, be similar in strength to those produced by potential prey items and may attract elasmobranchs by acting as phantom prey, particularly in the presence of olfactory cues that may be produced by actual prey nearby (Kalmijn, 1972; Kimber*, et al.*, 2011). The few studies that have quantified electric potentials around prey species present measurements in units that are not directly comparable to those discussed here. However, one of the rare converted measurements indicates that induced electric fields associated with bivalves and small crustaceans are generally less than 1000 nV cm^{-1} at 1 cm from the prey item (Haine*, et al.*, 2001; Kimber*, et al.*, 2011). Whilst attracting elasmobranchs may be considered a less concerning impact than deterring elasmobranchs, if attraction happens regularly and on a wide geographical scale, the potential negative impacts of EMFs around submarine power cables could range from reducing fitness at an individual through to a population level.

3.2.4 Choosing experimental parameters

Ideally, cables similar to those proposed for the Kaipara Marine Turbine Generation Project would be used (refer to Section 1.3.1), however, running cables rated at 350 A over a very short distance raises serious safety concerns, in addition to the prohibitive cost of sourcing such cables and the equipment that could safely generate close to 300 A of current for a sustained amount of time.

In view of these safety constraints, the experiments in this chapter constitute a preliminary investigation and were run at a much lower electrical current than would be found in the field, but that would still produce EMFs around the cable that would be within the rays' electrosensory detection range. If negative effects were found at a low current of 30 A, then effects would clearly also be likely at higher currents, however if negative effects were not observed at 30 A, further investigation at higher electrical currents would be required.

As 2.4 m s^{-1} is the maximum recorded water flow through the Kaipara Harbour channel, a lower water flow rate through the tank was required, as this would more realistically reflect the flow rates that occur most regularly, rather than the extreme, which only occurs periodically (during spring tides).

Due to the size and design of the experimental tank, it was unfeasible to achieve a consistent circular water flow higher than 0.2 m s^{-1}. However, it was found that at velocities above 0.15 m s^{-1}, eagle rays struggled to settle on the bottom and remain stationary, and were instead slowly swept around the tank. To avoid this unnatural stress for the animals the water flow through the experimental tank was set at 0.12 m s^{-1}.

3.2.5 EMFs around the chosen parameters

Table 3.1 shows the electric fields expected to be induced around a 30 A submarine power cable by seawater flowing perpendicular to the cable at a velocity of 0.12 m s^{-1}. Despite the lower electrical current through the power cable than would be the case in the field, the EMFs are still within the detection range of elasmobranchs. It was not possible to verify whether the expected, calculated fields were equivalent to those present. However, the calculated induced electric fields in Chapters Four and Five were verified and found to be accurate, so the calculations in this chapter are also expected to be accurate.

Table 3.1 – Expected induced EMFs around a 30 A submarine power cable by seawater flowing at a velocity of 0.12 m s^{-1} perpendicular to the cable, and at several distances from the cable. EMFs were calculated using Equations 2.1 and 2.3. If cable is resting on the seabed, 0° is perpendicular to the seabed (directly above cable) and 90° is parallel to the seabed. Burying or half-burying the cable does not affect the EMF strengths.

Distance from cable (m)	Angle	Induced EMF strength (nV cm^{-1})
0.01	0° (⊥ to seabed)	720.0
	30°	623.5
	45°	509.1
	60°	360.0
	90° (‖ to seabed)	0.0
0.05	0°	144.0
	30°	124.7
	45°	101.8
	60°	72.0
	90°	0.0
0.10	0°	72.0
	30°	62.4
	45°	50.9
	60°	36.0
	90°	0.0

As discussed in Chapter Two, an animal – in this case an eagle ray – is electromagnetically conductive, and will induce EMFs as it swims through the magnetic field around a submarine power cable. The EMFs induced by the animal will depend on its swimming speed and the angle at which it crosses the cable. The EMFs induced by an animal will be additive or subtractive to those already induced by any seawater flow, depending on whether the animal is swimming against or with the water flow.

In the case of no seawater flow across the cable and therefore through the magnetic field around it, theoretically no EMFs would be induced, except any induced by an animal swimming through the magnetic fields. However, the movement of the animal in the tank is likely to create some movement of seawater, and so some very weak EMFs are likely to be generated, though much weaker than those induced in experiments with seawater flow.

3.2.6 Study species: New Zealand eagle ray

The New Zealand eagle ray (*Myliobatis tenuicaudatus* Hector, 1877) is one of the most commonly found benthic elasmobranchs in New Zealand (Harthill, 1989). It is commonly found in estuarine environments, including the Kaipara Harbour. *M. tenuicaudatus* is thus highly likely to encounter the cables from the Kaipara Marine Turbine Generation Project, and may be susceptible to any effects from induced electric fields around the cables.

3.2.6.1 Taxonomy

Kingdom: Animalia
Phylum: Chordata
  Subphylum: Vertebrata: vertebrates
Class: Chondrichthyes: cartilaginous fish
  Subclass: Elasmobranchii: sharks, skates and rays
Order: Rajiformes: skates and rays
Family: Myliobatidae: eagle rays and manta rays
Genus: *Myliobatis* Cuvier, 1816
Species: *Myliobatis tenuicaudatus* Hector, 1877: New Zealand eagle ray

M. tenuicaudatus may be synonymous with the southern eagle ray (*M. australis* Macleay, 1881) found in southern Australia (Francis, *et al.*, 1987; Last & Stevens, 2009).

3.2.6.2 Morphology

New Zealand eagle rays have an olive green, yellow or dark brown dorsal surface with blue or light grey markings that differ between individuals and a white or pale yellow ventral surface (Cox & Francis, 1997; Davis, 2010). They have a rounded, fleshy rostrum and eyes protruding from the dorsal surface, just anterior to two large spiracles, which are used for gill ventilation and for creating a hydraulic jet used for foraging (Gregory, *et al.*, 1979). The mouth is ventrally-located, and eagle rays' teeth have evolved into fused broad crushing plates in each jaw that are used to break open the shells of their larger prey (Ayling & Cox, 1982).

M. tenuicaudatus has wide, pointed pectoral fins that are simultaneously flapped vertically like wings to swim. These features make *M. tenuicaudatus* easily distinguishable from other native New Zealand ray species – the short-tail stingray (*Dasyatis brevicaudata* Hutton, 1875) and the thorntail stingray (*D. thetidis* Ogilby, 1899) – which both undulate their more rounded wings to propel themselves forward (Cox & Francis, 1997; Taylor, 2000).

3.2.6.3 Range and habitat

M. tenuicaudatus is found around the North Island of New Zealand and as far north as Norfolk Island and the Kermadecs, though some specimens have also been recorded as far south as Kaikoura on the South Island (Francis, *et al.*, 1987; Cox & Francis, 1997). If *M. tenuicaudatus* is indeed conspecific with *M. australis*, then their range is more widespread and also extends to southern Australia and Tasmania, which would further bolster the likelihood of these rays encountering submarine power cables (Last & Stevens, 2009).

New Zealand eagle rays are found in coastal waters and on the inner continental shelf, from shallow waters (less than 5m) down to 100m. Their depth preference appears to vary with season, and they may migrate to deeper waters in the winter months, though there may also be some latitudinal migration, both of which increase the likelihood of these rays encountering submarine power cables (Harthill, 1989). However, observations in the Whangateau estuary, northern New Zealand, indicate that some individuals do overwinter in shallow coastal areas (Le Port, 2003).

3.2.6.4 Diet and feeding

M. tenuicaudatus frequently feeds on prey species that are known to burrow at least 20cm down into the sediment, indicating a high reliance on their electrosensory system to detect them. This is reflected in the morphological arrangement of the ampullary canals of the electrosensory system, which are largely concentrated on the ventral surface (Raschi, 1978; Tricas, 2001; Le Port, 2003; Jordan, 2008). Eagle rays access these prey by taking water in through their dorsal spiracles and forcefully jetting it out of their ventrally-located gills and mouth, clearing the substrate underneath. This foraging behaviour leaves behind distinctive feeding pits, sometimes with an imprint of the ray's body around the pit (Gregory*, et al.*, 1979; Le Port, 2003).

M. tenuicaudatus feeds on a variety of benthic invertebrates, seemingly predominantly over soft substrata. An ontogenetic shift in prey preference has been observed in a study of eagle ray stomach contents, with smaller individuals mainly consuming shrimps and smaller hermit crabs, but medium-sized individuals shifting towards gastropods and crabs, which also tend to be larger in size. The largest eagle rays in the study also consumed bivalves and polychaetes (Harthill, 1989). The study focused on eagle rays found over soft, sandy substrata so may be biased in its conclusions, as *M. tenuicaudatus* is also found over rocky reef substrata where it feeds on a wide variety of gastropods (Taylor, 2000; Le Port, 2003). Eagle ray feeding patterns can cause significant disturbance to the sediment and can have an important, albeit localised, impact on the structure and density of communities within the substratum (Hines*, et al.*, 1997).

Eagle rays in the Whangateau estuary were found to feed during both day and night, with some evidence of increased foraging intensity at night, which may simply reflect an avoidance of daytime disturbances from boats and swimmers or may indicate a preference for feeding at night. Regardless of time of day, foraging intensity increased at high tide and foraging activity was linked to tidal cycles (Le Port, 2003).

3.2.6.5 Predators

In New Zealand, resident killer whales (*Orcinus orca* Linnaeus, 1758) are known to regularly predate on native ray species, and are probably the main natural predator of *M. tenuicaudatus* (Visser, 1999). Other natural predators of *M. tenuicaudatus* include great white sharks (*Carcharodon carcharias* Linnaeus, 1758) (Duffy, 2003).

Whilst *M. tenuicaudatus* is not the target of any commercial fisheries, it is taken as fishing bycatch, predominantly by inshore trawls around the upper North Island as well as in Danish seine nets, set lines and drag and set nets. It is also caught by recreational anglers. *M. tenuicaudatus* is currently classified as a species of least concern by the IUCN (Duffy, 2003).

3.2.6.6 Life history and reproduction

New Zealand eagle rays are thought to reach maturity unusually slowly relative to other myliobatids with females probably reaching sexual maturity at around 18 years and males at around 8 years. Males are easily identifiable through the presence of two claspers underneath the tail, which are particularly prominent once sexual maturity has been reached (Harthill, 1989; Le Port, 2003).

New Zealand eagle rays are viviparous and their embryos are aplacental, but little else is definitively known about their reproductive cycle (Harthill, 1989; Cox & Francis, 1997). It is thought that they follow an annual reproductive cycle and that parturition, ovulation and mating probably all take place during late winter and spring (Le Port, 2003).

Some size segregation has been observed with juveniles generally found deeper than adults. There has also been some evidence of sexual segregation through winter observed in the Leigh area. As with size segregation, this is often observed in elasmobranchs and may relate to uses of certain areas as nursery grounds by females (Harthill, 1989).

3.3 Methods

3.3.1 Study animals

The eagle rays used in this study were caught and housed under University of Auckland Ethics Approval R817.

Three eagle rays were caught in the southern arm of the Kaipara Harbour between January and March 2011, using 30 m set nets with a 2-hour soak time. These three animals were initially caught for and used in a prior research project, and were already housed at the laboratory. A fourth eagle ray was caught as bycatch by RV Hawere whilst longlining for a different research project in Kawau Bay in April 2013 (refer to Table 3.2).

Table 3.2 – Details about each of the four NZ eagle rays that provided the data presented in this chapter, including sex, wing span, date and location caught and method used to catch them. ER1, ER2 and ER3 were previously used in experiments unrelated to this project.

Animal	Sex	Wing span (m)	Date caught	Location caught	Catch method
ER1: Bombay	F	0.57	26-01-2011	Kaipara Harbour	Set-netting
ER2: Winky	M	0.58	28-02-2011	Kaipara Harbour	Set-netting
ER3: Sapphire	F	0.50	29-03-2011	Kaipara Harbour	Set-netting
ER4: Beefeater	M	0.60	26-04-2013	Kawau Bay	Longlining

Since ER1, ER2 and ER3 were all already habituated to being in a tank environment at the lab and were all feeding well, they did not require any adjustment time. ER4 required three weeks to habituate to being in a tank and to start feeding consistently. Experiments were not run if the animals were not feeding as loss of appetite is an indicator of stress.

When not in the experimental tank, animals were kept in their own individual holding tanks, to prevent territorial fights or mating stress for the females. The holding tanks were circular, with a diameter of 2 m, and a water depth of 1.5 m. The holding tanks were covered with a layer of shade cloth to prevent the eagle rays from jumping out of their tanks at night, a relatively common problem with this species when kept in captivity. Each holding tank had a continuous flow of seawater and an air stone to provide an additional source of oxygen.

Animals were predominantly fed pilchard to maximise the effectiveness of using pilchard as an olfactory stimulus, but were also sometimes fed mussels or squid for variety. They were fed three times per week.

3.3.2 Experimental tank set-up

The experimental tank was circular, with a diameter of 2 m and a water depth of 55 cm. There was a circular plinth in the centre of the tank. Mesh fencing was set up around the outer periphery of the tank to prevent the previously-mentioned risk of eagle rays jumping out of their tanks at night. A camera was suspended above the tank to record all experiments. To maximise the contrast between the animal and the tank so that the animal would be clearly visible on the video footage, the tank was white.

As shown in Figure 3.1, a cable was run down one side of the tank, along the bottom and back out of the tank through the central plinth. On the opposite side of the tank, a length of flexible hose of similar diameter to the cable was set up in an identical configuration to act as a control when the cable power was ON, and a secondary control when the cable power was OFF. Before running experiments, it was not possible to know whether simply switching off the power to the cable would be suitable as a control, so the hose was added as an extra measure. If the rays showed similar responses to the hose and the cable with power OFF, then it could be concluded that the hose was not

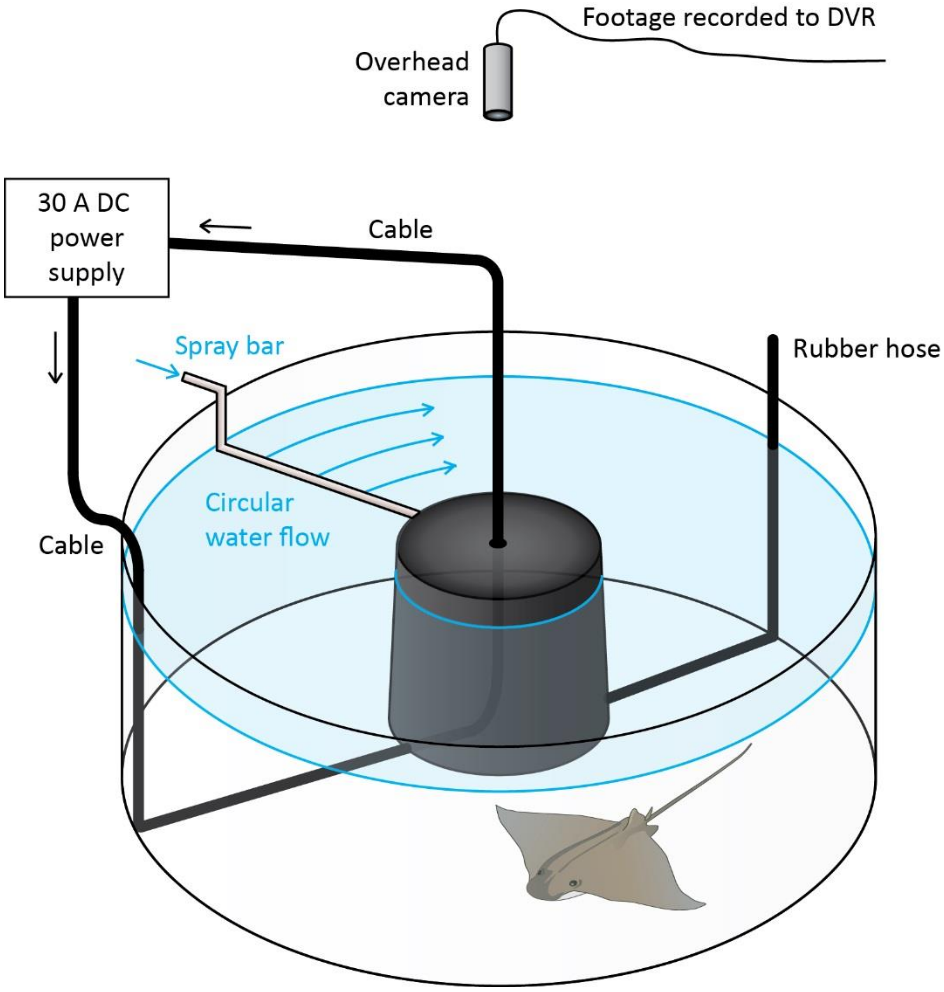


Figure 3.1 – Diagram of the set-up of the experimental tank, showing the electrical cable and the rubber control hose, placed on opposite sides of the tank. The cable returns to the power supply via the central plinth in the tank.

presenting a different visual or olfactory cue (due to it being made of a different material than the cable).

The cable was connected to a Powertech MP3094 switching mode power supply, which was set up to deliver a steady current of 30 A ± 0.2 through the cable when switched on.

The water flow through the tank was delivered through a spray bar at the top of the tank (shown in Figure 3.1) to create a circular water flow around the tank so that the water would be flowing as perpendicular as possible to the cable and was set so that the water velocity was 0.12 m s^{-1} over both the cable and control hose. The plinth in the middle of the tank helped to encourage this circular water flow and also prevented the eagle ray from crossing the centre of the tank and to maximise the number of encounters with the cable.

The seawater used in the experimental and holding tanks was pumped from the Goat Island Marine Reserve just outside the laboratory (this is the standard seawater supply for the Leigh Marine Laboratory). Seawater was delivered at ambient temperature, which ranged from 14.0 – 18.5°C over the course of experimentation. This temperature change was too small to significantly alter seawater conductivity over the course of experiments and impact results.

3.3.3 Experimental protocol

Experiments were conducted on each eagle ray individually. Animals were allowed to acclimatise to the experimental tank for at least two weeks before experimentation began. As loss of appetite is a common indicator of stress, animals who were otherwise behaving normally were considered acclimatised when they had eaten their food for at least two consecutive feedings.

Experiments were run for 20 minutes at a time. This was determined by the length of time that the power supply could be run safely in a tank room environment without overheating, but also maximising the likelihood of the experimental animal encountering the cable at least once during the experiment. An experiment started when the power supply was switched on and concluded when it was switched off. Control of the power supply was manual, and all experiments were timed.

Control experiments, where no current was running through the cable also lasted 20 minutes.

All experiments were both observed in person and filmed with an overhead camera, with the footage saved to a DVR. During the experiment, any behaviours of interest were noted down.

A maximum of three experiments were conducted in a day, with a resting period of at least two hours between experiments. On experimental days, two experiments were conducted with the power to the electrical cable switched on, and one experiment was conducted with the power switched off, to act as a control. The order of these was randomised from day to day.

To study whether responses to the EMFs around the cable differed when an animal was foraging, half of the experiments were conducted with an added olfactory stimulus to incite foraging.

Since the EMFs around submarine power cables are induced by the movement of electrically-conductive seawater, a number of experiments were also conducted with no water flow through the tank. It is, of course, unfeasible to completely still the water in a large tank, particularly when there is a moving animal within the water, but by cutting off the water flow two hours before experimentation the circular water flow around the tank was lost. The water was then considered to have "no flow" for EMF-inducing experimental purposes. When water flow to the tank was cut off, air stones were put in the tank to ensure the water was well oxygenated for the animal. It was necessary to remove the air stones whilst experiments were run as the bubbles created too much reflection on the water surface when filming experiments with the overhead camera.

3.3.4 Olfactory stimuli

Pilchard heads were steeped in fresh water for one hour and 20ml of this water was used as an olfactory stimulus per experiment. During preliminary testing of potential olfactory stimuli, animals showed a good response to this olfactory stimulus and responded with a distinctive foraging search behaviour, often including an increase in intensity of movement and a clear "search" movement pattern along the bottom of the tank. The olfactory stimulus was introduced into the water at the start of an experiment, at the same time as the power supply was switched on, using a syringe to aim it towards the bottom of the tank (where the eagle rays were located). In experiments where it was switched on, the water flow rapidly distributed the stimulus evenly through the tank.

As the animals consistently showed a good foraging response to the introduction of an olfactory stimulus, they were not starved prior to any experiments.

3.3.5 Categorisation of behaviours and analysis of results

The experimental animals were observed over many hours and in varied situations (after being moved to a new tank, whilst swimming around, whilst foraging, whilst feeding), and the range of behaviours exhibited were categorised. All experiments were observed in real-time, enabling immediate identification and classification of any additional behaviours.

As shown in the behavioural classification table (Table 3.3), observed behaviours fell into three broad categories: avoidance of the cable, investigation of the cable and ignoring the cable by crossing it.

Table 3.3 – Descriptions of how each of the various observed behaviours were categorised for data analysis.

Behaviour	Description & Examples
Repel/ Avoid	Animal clearly avoids the cable or is repelled by it Animal won't cross the cable, either by immediately changing direction or drastically changing position in the water column
Attract/ Investigate	Animal attracted to the cable and spends time over it, especially rostrum Investigates the cable (sharp turn/change of direction to search along it, or to swim back and forth along or over it) Behaviour similar to searching behaviour exhibited when foraging
Ignore/ Cross	Animal does not respond to cable/ignores cable Animal swims across the cable with no visible reaction

The recorded video of each experiment was watched, and the behaviour exhibited by the experimental animal during each encounter with the cable or control hose was categorised as one of the three behaviours in Table 3.3. The frequency of occurrence of each behaviour per experiment was recorded. The sharp turn towards the cable or hose associated with 'investigate' behaviour only ever occurred once the ray's rostrum was within 5 cm (determined through direct observation) of the cable or hose.

3.4 Results

Mann-Whitney U tests were conducted to determine whether during control experiments (where the power cable was switched off) the eagle rays showed a difference in response towards the switched-off cable and the hose. No significant differences were found for any of the treatments ($p > 0.05$ in all cases), so the data for the switched-off cable (OFF cable) and hose responses were pooled for analysis.

As shown in Table 3.4, many more behavioural interactions with both the cable and control hose were recorded under no flow conditions (2178 total behavioural interactions across 40 experiments) than under flow conditions (1342 total interactions across 49 experiments).

The mean frequencies of each behaviour are shown in Figure 3.2 for experiments with seawater flow and Figure 3.3 for experiments with no seawater flow. It is clear from both figures that both avoidance and investigatory responses occurred towards the active cable, but also towards the control hose and to both the control hose and switched-off cable in control experiments, and in the case of avoidance responses, seem relatively uniform across all experiments and controls, suggesting that avoidance is largely random. It is also clear that avoidance responses only made up a small proportion of all behavioural interactions (3.9% of behavioural responses across all experiments, compared to investigation and crossing which made up

17.9% and 78.2%, respectively), and that crossing the cable or hose is the predominant behaviour, especially in the experiments with no seawater flow.

Table 3.4 – Overview of the total number of behavioural responses shown towards the power cable and control hose across all 3520 observed interactions by four individual eagle rays over the course of 89 experiments. Power ON indicates experiments where the power cable was switched on, and the hose acted as a control. Power OFF indicates experiments where the cable was switched off, and the data for the switched-off cable (OFF cable) and the hose (which acted as a secondary control) have been pooled.

		No olfactory stimulus			**Olfactory stimulus**		
		Power ON to cable		**Power OFF**	**Power ON to cable**		**Power OFF**
	Behavioural response	**ON cable**	**Control hose**	**Hose + OFF cable**	**ON cable**	**Control hose**	**Hose + OFF cable**
Seawater flow	Cross (no response)	80	88	140	137	119	195
	Avoid	1	11	16	18	18	17
	Investigate	69	80	78	114	82	79
	Total	**150**	**179**	**234**	**269**	**219**	**291**
	Number of experiments	16	16	9	16	16	8
No seawater flow	Cross (no response)	186	516	277	259	431	325
	Avoid	4	9	8	15	10	11
	Investigate	22	4	15	37	35	14
	Total	**212**	**529**	**300**	**311**	**476**	**350**
	Number of experiments	14	14	6	14	14	6

The data for each response category (ON cable investigation, ON cable avoidance, ON cable non-response, control investigation, control avoidance and control non-response) were tested for a difference in distribution across the different experimental treatments (flow/no flow, olfactory stimulus/no olfactory stimulus, power on/off) using a Kruskal-Wallis test. As reported in Table 3.5, only the ON cable avoidance data was significantly affected by treatment ($p = 0.031$). All other responses showed no statistically significant differences in distribution across treatments.

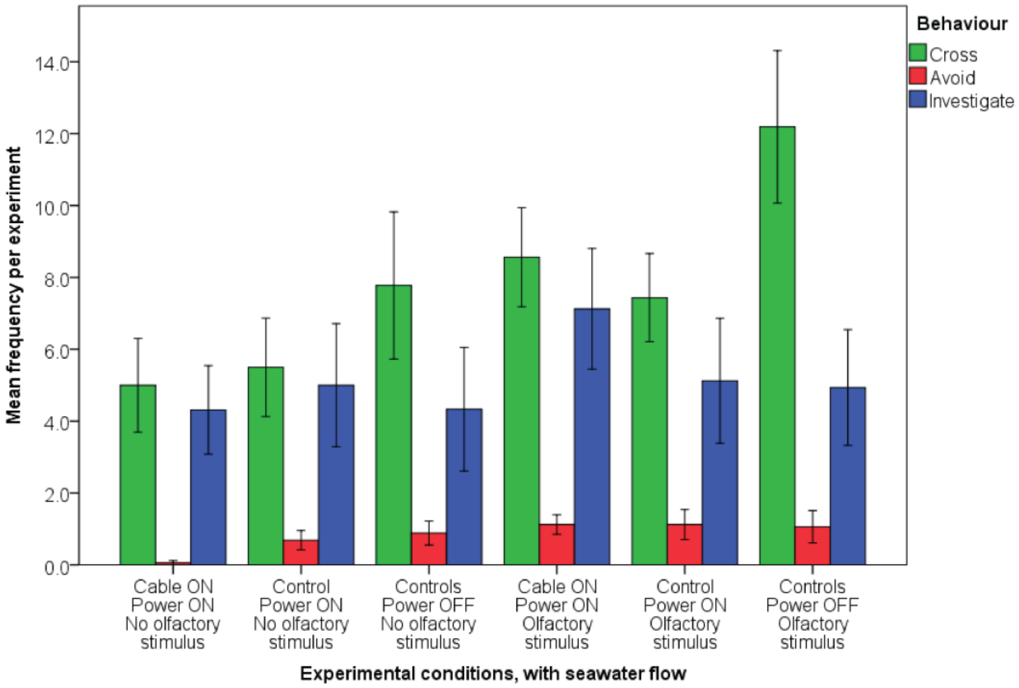


Figure 3.2 – Mean frequency (± 1 standard error) per experiment of each behavioural response (cross, avoid or investigate) towards the cable or control hose across each experimental treatment with seawater flow through the experimental tank. Power ON indicates experiments where the power cable was switched on (Cable ON), and the hose acted as a control (Control). Power OFF indicates experiments where the cable was switched off. The data are from four individual eagle rays across a total of 49 experiments.

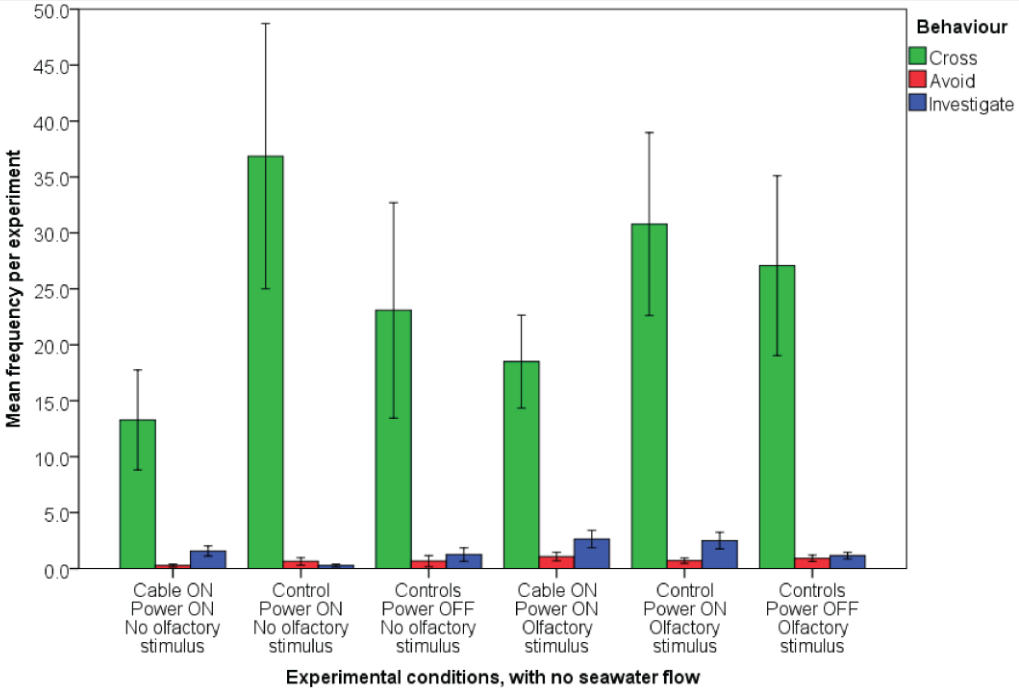


Figure 3.3 – Mean frequency (± 1 standard error) per experiment of each behavioural response (cross, avoid or investigate) towards the cable or control hose across each experimental treatment with no seawater flow through the experimental tank. Power ON indicates experiments where the power cable was switched on (Cable ON), and the hose acted as a control (Control). Power OFF indicates experiments where the cable was switched off. The data are from four individual eagle rays across a total of 40 experiments.

The ON cable avoidance data were *post-hoc* tested using Mann-Whitney U tests to ascertain the source of effect. Only selected treatments were compared (refer to Table 3.6). After applying a Bonferroni correction, the only significant difference in cable avoidance was found between experiments with seawater flow and an olfactory stimulus and experiments with seawater flow and no olfactory stimulus ($p < 0.001$), indicating that in conditions of seawater flow, the addition of an olfactory stimulus increased the frequency of avoidance of the active cable by the eagle rays.

It was observed during experiments that certain individuals were more active than others in particular conditions. ER4 was the least active animal, across all conditions. It is not possible to statistically test for differences across individuals in this case, so these are merely anecdotal observations.

Table 3.5 – *Post-hoc* analyses of data distribution for ON cable avoidance responses across selected experimental conditions, showing the Mann-Whitney U test statistic and statistical significance (p). When applying Bonferroni corrections per behavioural response * denotes statistical significance at the level $p < 0.00625 = 0.05/8$, ** at the level $p < 0.00125 = 0.01/8$.

Experimental treatment comparisons	U	*p*
Flow, No olfactory, Power ON *vs.* Flow, No olfactory, Power OFF	95.0	0.023
Flow, Olfactory, Power ON *vs.* Flow, Olfactory, Power OFF	107.0	0.40
No Flow, No olfactory, Power ON *vs.* No Flow, No olfactory, Power OFF	83.0	0.95
No Flow, Olfactory, Power ON *vs.* No Flow, Olfactory, Power OFF	0.00	1.00
Flow, No olfactory, Power ON *vs.* Flow, Olfactory, Power ON	53.0	**0.001****
No Flow, No olfactory, Power ON *vs.* No Flow, Olfactory, Power ON	67.0	0.10
Flow, No olfactory, Power ON *vs.* No flow, No olfactory, Power ON	87.0	0.11
Flow, Olfactory, Power ON *vs.* No Flow, Olfactory, Power ON	101.0	0.63

3.5 Discussion

As reported in Table 3.4 and clearly shown in Figures 3.2 and 3.3, avoidance behaviours were observed towards both the cable and the control hose, regardless of whether the cable was switched on or off. This suggests that the avoidance behaviour was either random or prompted by the visual cue of seeing the black cable or control hose against the white tank or the tactile cue of feeling the cable or control hose rising from the otherwise uniform floor of the tank. In fact, the lowest frequency of avoidance behaviours was observed in flow conditions when the cable was switched on. Clearly, the EMFs around this particular cable are not aversive to eagle rays.

The predominant behaviour shown by the eagle rays towards both the cable and control hose was to cross them – in seawater flow conditions, they crossed the switched-on cable 51.8% of the time, and they crossed the switched-off cable and control hose 58.7% of the time, but in no seawater flow conditions these proportions jumped to 85.1% and 93.6% of the time for crossing the active cable and the controls, respectively. This also ties in to a decrease in investigation frequency and an increase in the overall number of behavioural interactions with both the cable and control hose in no-flow conditions (compared to seawater flow conditions).

This distinct increase in the non-response (crossing) proportion of behavioural interactions both with the cable and control hose in conditions of no water flow compared to conditions of water flow suggest that the increase in activity was not exploratory – should that have been the case, an increase in behavioural response (whether avoidance or investigatory) to the active cable would have been expected. It is not clear whether the increase in activity was due to the rays being agitated due to the lack of water flow, or because the presence of water flow causes the rays to spend more time sitting on the bottom of the tank in order to conserve energy that would be expended swimming against the water current.

The rays showed distinctly more investigation than avoidance, as reported in Table 3.4 and shown in Figures 3.2 and 3.3, however, they showed investigatory behaviours towards both the active cable and the control hose (and switched-off cable), and no significant differences in investigation frequency across different treatments (including controls) were found. This suggests that, much like avoidance, the investigatory behaviour shown by the rays was either largely random or may have been prompted by the visual cue of being able to see the black cable and control hose, or the tactile cue of being able to feel them.

After *post-hoc* testing, the only significant difference in behaviour towards the active cable to be found due to different treatments was in the avoidance response data and was found between the olfactory and non-olfactory experiments in seawater flow conditions. If the eagle rays were showing a distinct response to the EMFs around the active power cable, a significant difference between responses to the active cable and the controls (whether the control hose or the switched-off cable) would have been expected, in both the avoidance and the investigatory data. Furthermore, a decrease in the non-response (or ignoring/crossing) to the cable in experiments with the cable switched on compared to those with the power switched off would also have been expected, with a greater frequency of non-response during experiments with the power off.

It is important to note that the statistical power of these analyses is very low, considering the limited number of experiments run with some of the treatments (such as the no flow, no olfactory, no power condition), and consequently the results of these analyses are strongly conservative. The small sample size of only four eagle rays also contributes to the low statistical power, but is limited by the availability of both the animals themselves and the facilities required to house them ethically.

Another important consideration is the potentially confounding issue that the cable and control hose were both black and the experimental tank was white, providing a strong contrast between the two, which the animals would have been able to see, despite their dorsally-located eyes (McComb & Kajiura, 2008; Gardiner, *et al.*, 2012). It is impossible to determine whether any behavioural responses were provoked by the weak EMFs around the electrical cable or this visual cue. Whilst rays do not rely strongly on visual cues whilst foraging for buried prey due to their morphology, it is not unreasonable that such a high-contrast visual cue could have an effect (Tricas, 2001; Le Port, 2003).

Additionally, the cable and hose both sat directly on and were thus raised relative to the otherwise uniform tank bottom, creating a clear tactile cue for the animals to detect and potentially respond to. Elasmobranchs detect tactile cues through the non-pore canals of their mechanosensory lateral line canal system (Maruska & Tricas, 2004). In rays, these non-pore canals are generally concentrated ventrally around the mouth area. Whilst the bat ray (*Myliobatis californica* Gill, 1865), which is closely related to *M. tenuicaudatus*, was found to have a smaller proportion of non-pore canals than two other ray species, and may thus be overall less sensitive to tactile cues than other species, the cable or hose raised above the bottom of the tank is likely to have been a large enough tactile cue for the animals to detect (Jordan, *et al.*, 2009b).

Whilst the 30 A electrical current passing through the power cable during experiments was well below the level of electrical current generally expected to be flowing through most submarine power cables, the expected induced EMFs around the electrical cable (given in Table 3.1) were well within the detection range of elasmobranchs, who have shown responses to fields as weak as 5 nV cm^{-1} (Kalmijn, 1982). Additionally, the closely-related *M. californica* has been found to show clear feeding responses to electric fields weaker than 10 nV cm^{-1}, so it is likely that *M. tenuicaudatus* was able to detect the EMFs in the experimental tank (Jordan, *et al.*, 2009a). However, if the presence of the EMFs was causing a behavioural response in the animals, we would have expected to see a significantly greater behavioural responses to the cable when the power was on, than when the power was off, and little or no behavioural responses to the control hose during either condition. This was clearly not the case, and the animals showed investigation and avoidance of the cable when the power was off, and showed both investigation and avoidance of the control hose in all experiments. The lack of variation in the data for hose response and non-response may indicate a baseline level of investigatory curiosity in the animals. As previously mentioned, this may also be an artefact caused by the tactile and/or high-contrast visual cues of both the cable and control hose, and further experiments would benefit from removing these visual and tactile cues.

In summary, whilst *M. tenuicaudatus* did show some investigatory and avoidance behaviour towards the cables when the power was switched on, which would suggest a behavioural response to the weak EMFs induced around the electrical cable in seawater, they also showed similar responses to the cable when it was switched off and also to the control hose. Consequently, these responses are likely to have been prompted by tactile cues from the animals feeling the cable or control hose, or by visual cues produced by the high contrast between both the cable and control hose against the tank. Further investigation with a modified experimental design and cables with electrical currents more comparable in strength to those used in the field is required.

CHAPTER FOUR:

THE IMPACTS OF SUBMARINE ALTERNATING CURRENT POWER CABLES ON BENTHIC SHARKS

4.1 Abstract

The electromagnetic fields (EMFs) generated around submarine alternating current (AC) power cables fall within the detection range of the extremely sensitive elasmobranch electrosensory system, and consequently may have a negative behavioural impact. The effects of AC power cables on New Zealand carpet sharks (*Cephaloscyllium isabellum* Bonnaterre, 1788) were studied in the laboratory using EMFs equivalent to those that would be found around a 50 Hz cable with a maximum electrical current of 100 A and a perpendicular 0.10 m s^{-1} seawater flow. The sharks showed no response to the EMFs around the active cable an overwhelming 98.2% of the time, and avoidance of the cable occurred more often when the cable was switched off than switched on, so was considered random. Only one instance of undirected swimming was observed out of a total of 526 behavioural interactions with the cable. Consequently, it is concluded that submarine AC power cables do not have an effect on this benthic species under these experimental conditions and are unlikely to be an issue for elasmobranchs in the wild.

4.2 Introduction

4.2.1 Use of submarine AC power cables

As explained in Chapter Two, power cables can either be direct current (DC), where the polarity of the current stays constant, or alternating current (AC), where the polarity constantly switches at a certain frequency. This chapter investigates the impacts of AC power cables on the behaviour of benthic elasmobranchs; for the impacts of DC power cables, refer to Chapter Five.

The continuously changing polarity of AC cables reduces the amount of power that an AC cable can transfer compared to a similarly-rated DC cable. Thus, AC cables are usually less cost-effective over long distances than DC cables, and are consequently used less often and generally only over distances shorter than 40 km, though this varies depending on the specifications of the cables, and longer submarine AC cables are in use and development, notably in the North Sea (Macleod*, et al.*, 2010; Thibaut & Leforgeais, 2015).

Due to the nature of AC, an AC cable always has a return current. Theoretically, the induced magnetic field around the cable would be expected to be nullified by that induced by the return current (C. Tindle, pers. comm., 2015, University of Auckland). In reality, however, due to inconsistencies in the cables, either because the conductors within the cable are not perfectly aligned, or there is an asymmetric rotation of the AC field within the cable, weak magnetic fields are present, and have been approximately modelled for buried three-phase submarine AC power cables (Normandeau*, et al.*, 2011). Consequently, very weak electromagnetic fields (EMFs) are likely to be induced around submarine AC cables by the movement of electrically-conductive seawater. Given the high sensitivity of their electrosensory system, such weak EMFs may still be detected by and consequently affect benthic elasmobranchs.

4.2.2 Electrosensory system of elasmobranchs

The elasmobranch electrosensory system is extremely sensitive, with behavioural responses shown to electric fields as low as 5 nV cm^{-1} (Kalmijn, 1982). The accuracy and short-range efficacy of this sense makes it especially useful for pinpointing the weak electric fields produced by hidden prey or conspecifics (Kalmijn, 1971, 1982; Tricas*, et al.*, 1995). The sensitivity of the electrosensory system varies across species, and is particularly developed in benthic species which may feed on prey hidden in sediment, and is likely to also be very important to species that are nocturnal or live in turbid environments, where vision is limited (Jordan, 2008; Jordan*, et al.*, 2009a;

Kajiura*, et al.*, 2010; Egeberg*, et al.*, 2014; O'Connell*, et al.*, 2014c; Kempster*, et al.*, 2016b).

Weak electric fields in the seawater are detected through electrosensory pores called ampullae of Lorenzini, shown in Figure 1.2A. In sharks, these are generally concentrated around the head and mouth, as demonstrated in Figure 1.2B, which shows the distribution of electrosensory canals leading from the ampullae of Lorenzini in the lesser spotted dogfish (*Scyliorhinus canicula* Linnaeus, 1758), a small benthic dogfish common in the northeast Atlantic (Ellis*, et al.*, 2005; Gardiner*, et al.*, 2012).

The electrosensory system responds to differences in electrical potential between an internal reference potential and the potential of an external stimulus at the pore opening. This difference in electrical potential is detected across the sensory epithelium of the alveoli within the ampullae of Lorenzini, shown in Figure 1.2A (Sisneros & Tricas, 2002). For more detail about the electrosensory system and the ampullae of Lorenzini, refer to Section 1.4.

One of the key considerations for the potential impact of AC currents is the extent to which they match the frequency characteristics of the elasmobranch electrosensory system. Figure 4.1 shows frequency response

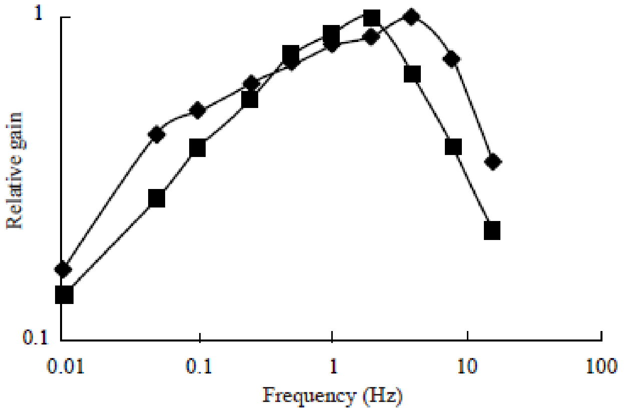


Figure 4.1 – Frequency response curve for the primary afferent electrosensory neurons in the round stingray (squares) and the thornback guitarfish (diamonds), showing a distinct peak in response between 2 and 4 Hz, and a clear drop-off in response after 4 Hz (from Montgomery & Bodznick, 1999).

curves for the round stingray (*Urolophus halleri* Cooper, 1863) and the thornback guitarfish (*Platyrhinoidis triseriata* Jordan & Gilbert, 1880) show peak responses around 2 and 4 Hz, respectively (Montgomery, 1984a; Tricas, *et al.*, 1995; Montgomery & Bodznick, 1999). Considering the clear drop in response above 4 Hz for these two ray species, response sensitivity is expected to be low in the 50 Hz range. However, given that no response data are shown above 16 Hz and the elasmobranch electrosensory system is known to be extremely sensitive, sensitivity in the 50 Hz range cannot be discounted, and is worth verifying.

In addition to having a more sensitive electrosensory system, benthic elasmobranch species are also significantly more likely to encounter submarine power cables, and thus more likely to be impacted by the weak EMFs generated around them in seawater (refer to Chapter Two for more detail on the generation of these EMFs).

4.2.3 Expected impacts of AC power cables on elasmobranchs

The EMFs around many submarine power cables fall within the very sensitive electrosensory detection range of elasmobranchs (refer to Chapters One and Two). As a result, these EMFs may have a behavioural impact on any elasmobranchs that encounter them by either repelling the animals or, more likely, attracting them.

The use of electric fields and permanent magnets to deter elasmobranchs, particularly in relation to fishing gear in order to reduce bycatch, has been studied with varying success (O'Connell*, et al.*, 2010; Howard, 2011; O'Connell*, et al.*, 2011). However, the fields and magnetic strengths used are deliberately at the upper end of the elasmobranch detection range in order to overwhelm the electrosensory system and make the animals uncomfortable (Howard, 2011). The EMFs around submarine AC power cables are usually several orders of magnitude weaker than those used in deterrent devices, and are thus not expected to deter benthic elasmobranchs from crossing any cable zones.

However, since the EMFs induced around submarine AC power cables are at the lower end of the elasmobranch electrosensory detection range, they may coincide with those produced by prey species. When given a choice between a simple artificially-produced field and a complex bioelectric field produced by its usual prey, *S. canicula* did not show a preference in the absence of any visual cues (Kimber*, et al.*, 2011). Consequently, benthic elasmobranchs foraging near submarine AC power cables may mistake the induced EMFs for an indication of prey, particularly in the presence of olfactory cues indicating that hidden prey is present. Over time, this may have an impact on the fitness of individuals if energy resources are regularly wasted on foraging around submarine power cables acting as phantom prey.

4.2.4 Choosing experimental parameters

Experiments were run to replicate the conditions around an AC cable delivering current at a frequency of 50 Hz as this is the frequency at which AC is distributed within New Zealand. The strength of the electrical current was kept as close as possible to the electrical current strength in the DC experiments in Chapter Five in order to maximise their comparability, but was restricted by safety concerns.

The safety concerns discussed in Chapter Three regarding running power cables at voltages and electrical currents that would be used for power transmission over a short distance in a laboratory setting were resolved by using the additive property of magnetic fields. A single 2 × 2.5 mm^2 double-core power cable was looped around the same path multiple times so that the magnetic fields around each loop of the cable combined to approximate the magnetic field that would be generated by a single power transmission cable of the specifications required. This meant that the cable could be run with a much lower (and significantly safer) electrical current than the field cable being simulated.

Seawater flow for the experiments was set to 0.10 m s^{-1} perpendicular to the cables. Higher rates of water flow in the experimental tank resulted in the experimental sharks being swept around the tank rather than being able to settle on the bottom as they normally would.

4.2.5 EMFs around the chosen experimental parameters

Due to the complex nature of the EMFs generated around submarine AC power cables in seawater, it is difficult to exactly calculate the EMFs. The magnetic field generated around the experimental cable set-up was measured using a hall-effects sensor and the maximum magnetic flux density was measured to be 1.43×10^{-3} T, though this measurement comes with a large error of margin due to the weakness of the fields, and so the upper and lower bounds of error are 2.00×10^{-3} T and 1.14×10^{-3} T respectively. The measurements were taken at the tank bottom directly above the cables, in still, ambient seawater. The tank bottom was measured to be 10 mm thick and was not found to impede the EMFs. The measured magnetic flux density was approximately 80 times the highest flux density modelled by Normandeau*, et al.* (2011) for cables buried 1 m below the seabed. The multiple loop cable set-up may also have increased the measured magnetic flux density.

The above magnetic fields would correspond to those generated around a cable with 75 A running through it, with upper and lower bounds of 100 A and 57 A respectively. Table 4.1 shows the electric field strengths that would be expected to be induced by a seawater flow perpendicular to the AC cables with a velocity of 0.10 m s^{-1}, based on the above measurement of a typical magnetic flux density of 1.43×10^{-3} T and the measurements taken of the seawater velocity throughout the experimental tank.

Table 4.1 – Electric field (EF) strengths around the experimental AC power cable expected to be induced by seawater flowing at a velocity of 0.10 m s^{-1} perpendicular to the cable and at several distances from the cable. EFs were calculated using Equations 2.1 and 2.3 and measures of a magnetic field of 1.43×10^{-3} T induced by the AC cable in the experimental tank. If cable is resting on the seabed, 0° is perpendicular to the seabed (directly above cable) and 90° is parallel to the seabed. Burying or half-burying the cable does not affect the EMF strengths.

Distance from cable (m)	Angle from seabed	Induced EF strength (nV cm^{-1})
0.01	0° (⊥ to seabed)	1430.0
	30°	1238.4
	45°	1011.2
	60°	715.0
	90° (‖ to seabed)	0.0
0.05	0°	286.0
	30°	247.7
	45°	202.2
	60°	143.0
	90°	0.0
0.10	0°	143.0
	30°	123.8
	45°	101.1
	60°	71.5
	90°	0.0

4.2.6 Study Species: New Zealand carpet shark

The New Zealand carpet shark (*Cephaloscyllium isabellum* Bonnaterre, 1788), also known as the draughtsboard shark, is a small benthic shark endemic to New Zealand. It is a relatively common species, and is found in a variety of habitats throughout New Zealand. Due to its benthic and opportunistic nature, as well as its broad geographical range throughout New Zealand, *C. isabellum* is likely to encounter submarine power cables.

4.2.6.1 Taxonomy

Kingdom: Animalia
Phylum: Chordata
    Subphylum: Vertebrata: vertebrates

Class: Chondrichthyes: cartilaginous fish
Subclass: Elasmobranchii: sharks, skates and rays
Order: Carcharhiniformes: ground sharks
Family: Scyliorhinidae: cat sharks
Genus: *Cephaloscyllium* Gill, 1862: swell sharks
Species: *Cephaloscyllium isabellum* Bonnaterre, 1788: New Zealand carpet shark

4.2.6.2 Morphology

New Zealand carpet sharks have rough skin which is light brown dorsally with irregular, dark brown spots and saddles, and cream to yellowish ventrally with few or no markings. They have elongated, cat-like eyes, which is a distinct feature of the Scyliorhinidae. Whilst not considered dangerous, their teeth can still do damage. *C. isabellum* is a small shark – adults can reportedly reach up to 150 cm total length, but individuals are rarely seen above 100 cm (Cox & Francis, 1997; Francis, 2012).

4.2.6.3 Range and habitat

C. isabellum is endemic to New Zealand and found throughout the country's coastal waters, including Stewart Island and the Chatham Islands and Snares Islands. It is considered common all through its range, down to a depth of 673 m, though most individuals are found above 400 m (Francis, 2003, 2012). Its depth range appears variable around New Zealand, which is likely temperature-driven.

New Zealand carpet sharks are found in a variety of habitats, ranging from rocky areas to sand flats, and are thought to travel between them, probably diurnally (Cox & Francis, 1997; Francis, 2012). This regular movement between various habitats may increase the likelihood of carpet sharks encountering submarine power cables, thus increasing the possibility of impacts.

4.2.6.4 Diet and feeding

New Zealand carpet sharks are nocturnally active noctu and generally travel to sand flats to feed. They are largely opportunistic and diverse feeders, and are known to eat fish, crustaceans and cephalopods, as well as other bottom-dwelling invertebrates (Cox & Francis, 1997; Francis, 2012). Given that this species principally forages over sand flats where prey may more easily bury itself, and also does so at night, it is likely to be quite reliant on its electrosensory system to detect and pinpoint prey. The closely-related swellshark (*Cephaloscyllium ventriosum* Garman, 1880) has been demonstrated to rely on electroreception for detecting prey that ventured too close to the shark's mouth at night (Tricas, 1982).

4.2.6.5 Predators

The main natural predators of *C. isabellum* are likely to be larger opportunistic sharks. Neonatals and juveniles are likely vulnerable to larger fish such as snapper (*Chrysophrys auratus* Forster, 1801), though little information exists about specific predation threats to this species.

Whilst *Cephaloscyllium isabellum* was fished as part of a shark liver fishery from 1988-1991, it is no longer a targeted species and annual catches are less than five tonnes per annum, most of which is thought to be discarded. It is a common bycatch species in the rock lobster fishery, as well as in trawls, but post-release survival rates are thought to be high. *C. isabellum* is currently classified as a species of least concern by the IUCN (Francis, 2003).

4.2.6.6 Life history and reproduction

The New Zealand carpet shark reaches sexual maturity at 60 cm total length for males, and 80 cm for females (Francis, 2003). Males are easily identified by the presence of two claspers between their anal fins, which are particularly prominent once sexual maturity has been reached. Information on growth rates for this species is not available, so it is not known at what equivalent ages sexual maturity is reached.

C. isabellum is an oviparous species, and lays pairs of rectangular, yellow-beige egg cases which are tough and have spiral tendrils at each corner to anchor the eggs to seaweed or other objects (Francis*, et al.*, 1987; Cox & Francis, 1997). The eggs take between 6-12 months to develop and hatch, which seems temperature-driven. Females lay a pair of eggs every 3-4 weeks, and, in captivity at least, this does not appear to be seasonally-dependant (pers. obs.). Little else is known about reproduction in this species.

Based on the sex distribution of the individuals caught for both this chapter and Chapter Five, it is highly likely that size segregation occurs in this species, which is relatively frequent in elasmobranchs (Conrath & Musick, 2012).

4.2.6.7 New Zealand carpet sharks as a study species

C. isabellum is a particularly good laboratory species as they acclimatise to new tanks quickly, return to normal behaviour quickly post-handling and do not appear unduly stressed by captivity. Thus their behaviour in the experimental tanks is likely to reflect the behaviour they would show in the wild.

4.3 Methods

4.3.1 Study animals

The carpet sharks used in these experiments were caught and housed under University of Auckland Ethics Approval number 001284.

Table 4.2 – Details of the six New Zealand carpet sharks caught for the experiments presented in this chapter, including sex, nose-to-tail length, date caught and method used to catch them. The locations are as reported by the fishermen who caught the animals. Only CS7, CS8, CS9 and CS10 were used for experiments

Animal	Sex	Length (m)	Date caught	Location caught	Catch method
CS7: Aberfeldy	F	0.73	17-10-2014	Little Barrier Island	Cray-pot by-catch
CS8: Balblair	F	0.72	17-10-2014	Little Barrier Island	Cray-pot by-catch
CS9: Clynelish	F	0.70	04-11-2014	Leigh Reef	Cray-pot by-catch
CS10: Dalmore	F	0.72	14-11-2014	Cape Rodney Reef	Cray-pot by-catch
CS11: Edradour	F	0.70	14-11-2014	Cape Rodney Reef	Cray-pot by-catch
CS12: Oban	F	0.71	14-11-2014	Cape Rodney Reef	Cray-pot by-catch

All of the animals were caught as by-catch in the cray-pots of local cray fishermen working out of Leigh harbour in October and November 2014 (refer to Table 4.2). Animals were brought to Leigh wharf by the fishermen, where they were collected. They were transported for the ten-minute drive to the Leigh Marine Laboratory in lidded transportation tanks filled with seawater and transferred to a large holding tank to acclimatise to laboratory conditions.

Each shark was tagged upon arrival in order to easily differentiate individuals in the holding tank. The tags were made out of white PVC or black polyethylene in different shapes and were sized appropriately to the sharks. They were fitted through either of the sharks' pectoral fins using sterilised plastic bolts and nuts through a hole made with a sterilised sharp leather hole-puncher. The healing of the hole was monitored and no infection ever occurred. Once identification of individuals was no longer required (after experimentation), the tags were easily removed by unblocking the nut, and the remaining hole healed over quickly.

Once an individual was feeding consistently and showed no other signs of stress, it was considered acclimatised to the laboratory environment. All animals acclimatised within ten days of arriving at the laboratory. Experiments were not run if animals were not feeding since loss of appetite can be indicative of stress (Charbeneau, 2004).

No fighting or territoriality was observed amongst the sharks, so when animals were not in the experimental tank, they were kept together in the same holding tank, a large circular tank of 2 m diameter and 1.5 m water depth. The holding tank had a continuous flow of seawater and two air stones provided extra aeration of the water.

Over the summer and early autumn, the seawater to both the holding and experimental tanks was cooled to 18°C or below as the sharks were observed to show signs of heat stress at water temperatures above 19°C. The ambient seawater temperature over the rest of the year was sufficiently cool for the sharks to be comfortable and exhibit normal behaviour.

The sharks were fed chopped-up pilchard to maximise the efficiency of using ground pilchard as an olfactory stimulus, but were also occasionally fed mussels for variety. They were fed twice per week.

Only CS7, CS8, CS9 and CS10 were used for experiments.

4.3.2 Experimental tank set-up

The experimental tank was circular, with a diameter of 2 m and a water depth of 0.55 m, and made of plastic, thus removing any possible interaction between the tank and the EMFs. There was a circular plinth in the middle of the tank. A camera was suspended above the tank to record all experiments, and to maximise the contrast between the animal and the tank bottom, the tank was white.

New Zealand carpet sharks are more active at night, so the experimental tank was set up in a room with a reversed night/day cycle so that experiments could be run when the sharks are most active. A red light was on during the day to enable us to see whilst running experiments and to allow the camera to film (the camera was also equipped with infra-red lights to further aid filming), and normal lights came on during the night to simulate daylight. Dusk and dawn were also simulated, as abrupt transitions between "night" and "day" conditions have been known to cause undue stress to animals in captivity and cause consequent strange behavioural responses (Charbeneau, 2004; Choromanski, 2004). The holding tank was in the same night/day cycle-reversed room to maximise the time that animals had to acclimatise to the reversed circadian cycle before transferral to the experimental tank, and minimise any unforeseen effects of the reversed circadian rhythm.

As shown in Figure 4.2, two separate cables were laid underneath the tank. This removed the issue of both visual and tactile cues potentially confounding results as discussed in Chapter Three (refer to Section 3.5). These cables were both connected to the same power supply such that only one or neither of the cables could be switched on at any given time. The Powertech MP3094 switching mode power supply was set up to deliver a consistent DC voltage of 13.0 V. A 50 Hz sinusoidal sound wave sound file was generated through MatLab, and loaded onto an MP3 player. This was used as the signal generator, and an amplifier was used to amplify the power of the signal through the connected cable (A or B).

Constant seawater flow entered the tank through a spray bar with angled holes in order to achieve circular water flow through the tank. The outflow was located in the centre of the tank, under the plinth. Circular water flow ensured that the seawater crossed through the magnetic field induced around the power cables as perpendicularly as possible, simplifying

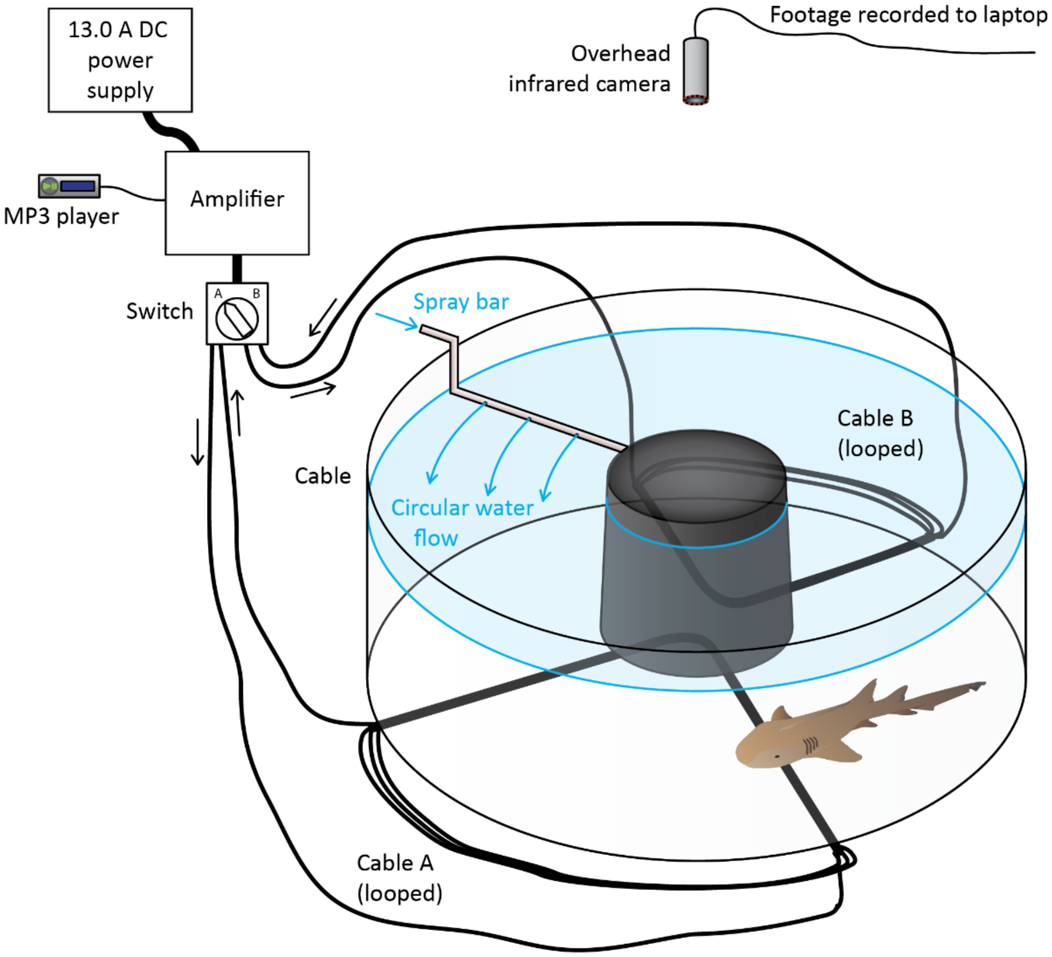


Figure 4.2 – Diagram of the experimental tank set-up, showing the two separate cables (A and B) underneath the tank, each looped around multiple times to increase the strength of the magnetic field generated around them. Both cables cannot be switched on at the same time. Power is delivered from a DC power source and the MP3 player plays a 50 Hz sinusoidal sound wave. The amplifier amplifies the power of the signal to the required strength and on to whichever cable is connected. Circular seawater flow was at a constant average velocity of 0.10 m s^{-1} at the bottom of the tank directly over the cables.

predictions of the electric fields induced by the movement of the seawater. The velocity of the seawater at the bottom of the tank directly over each of the cables averaged 0.10 m s^{-1}.

The seawater used in the experimental and holding tanks was pumped from the Goat Island Marine Reserve just outside the laboratory (this is the standard seawater supply for the Leigh Marine Laboratory). Seawater was cooled to 18°C in summer and delivered at ambient temperature in winter, so the temperature ranged from 14.0 – 18.0°C over the course of experimentation. This temperature change was too small to significantly alter seawater conductivity over the course of experiments and impact results.

4.3.3 Experimental protocol

Experiments were conducted on each carpet shark individually. Animals were given at least one week to acclimatise to the experimental tank before beginning experimentation. As loss of appetite is a common indicator of stress, animals were considered acclimatised after they had fed for at least two consecutive feedings, unless abnormal behaviour was observed. Abnormal behaviour was judged on observation of behaviour of the carpet sharks in the holding tank prior to being transferred to the experimental tank.

Each experiment lasted 20 minutes, which was determined by the length of time for which the power supply and amplifier could be run safely in a tank-room environment whilst also maximising the likelihood of the experimental animal encountering the EMFs around the cable over the course of an experiment. The switching-on of the power supply marked the start of an experiment, and the experiment ended when the power supply was switched off. Control of the power supply was manual, and all experiments were timed. No experiments were required to end early due to signs of distress from the shark.

Control experiments, where no electrical current was running through either cable also lasted 20 minutes and followed the same procedure as experiments with power.

All experiments were observed both in person and also recorded on an overhead camera with infra-red capabilities in order to film the experiments under red light to simulate night-time. The footage was recorded and saved to a laptop using iSpy v6.0.0.0 software. Any behaviours of interest observed directly during experimentation were noted.

No more than three experiments were conducted per day, with a resting time of at least 2.5 hours between each experiment. On experimental days one experiment was run with Cable A switched on, one experiment was run with Cable B switched on and one control (neither cable switched on) was run. The order of experiments was randomised so that the order of experiments changed from day to day.

Half of all experiments were conducted with the addition of an olfactory stimulus in order to investigate differences in response to the induced EMFs around a cable when an animal was foraging versus normal behaviour.

The experimental tank's air stone was removed during experiments as the bubbles created too much reflection on the water surface and interfered with the clear filming of the experiments. The seawater turn-over of the experimental tank maintained oxygen levels within the tank at a satisfactory level during the temporary removals of the air stone.

4.3.4 Olfactory stimuli

One pilchard was defrosted in fresh water for 30 minutes and then blended up in a food processor with enough of the defrosting water to create a liquid. 20 ml of this blended pilchard water was used as an olfactory stimulus per experiment. The olfactory stimulus was introduced into the tank using a syringe at the start of the experiment when the power supply was switched on, or, in the case of control experiments, at the allotted start time of the experiment. The circular water flow in the tank ensured that the stimulus was quickly distributed throughout the tank and water column.

During preliminary testing of the use of pilchard as an olfactory stimulus, animals showed a good response with a distinct change in behaviour with a searching pattern around the bottom of the tank. However, over time some animals stopped responding to the olfactory stimulus. Other olfactory stimuli were tested (mussels and squid) but animals showed little or no response. CS9 was starved prior to olfactory experiments, but this did not make a difference either. Consequently, normal feeding was resumed, since starving had no effect and was more likely to just cause unnecessary stress to the animal.

4.3.5 Categorisation of behaviours and analysis of results

The experimental animals were observed in a range of situations (including whilst in the holding tank, after being moved to a new tank, whilst foraging and whilst feeding), and behavioural characteristics were noted and categorised. The observation of behaviour in real time during experiments allowed for any previously un-observed behaviours to be added to the behavioural classification table.

Post-experiment, the recorded videos of each experiment were watched and the behaviour shown by the experimental animals in each interaction with the cable zones was categorised as one of the four behaviours described in Table 4.3. The frequency that each behaviour occurred per experiment was recorded.

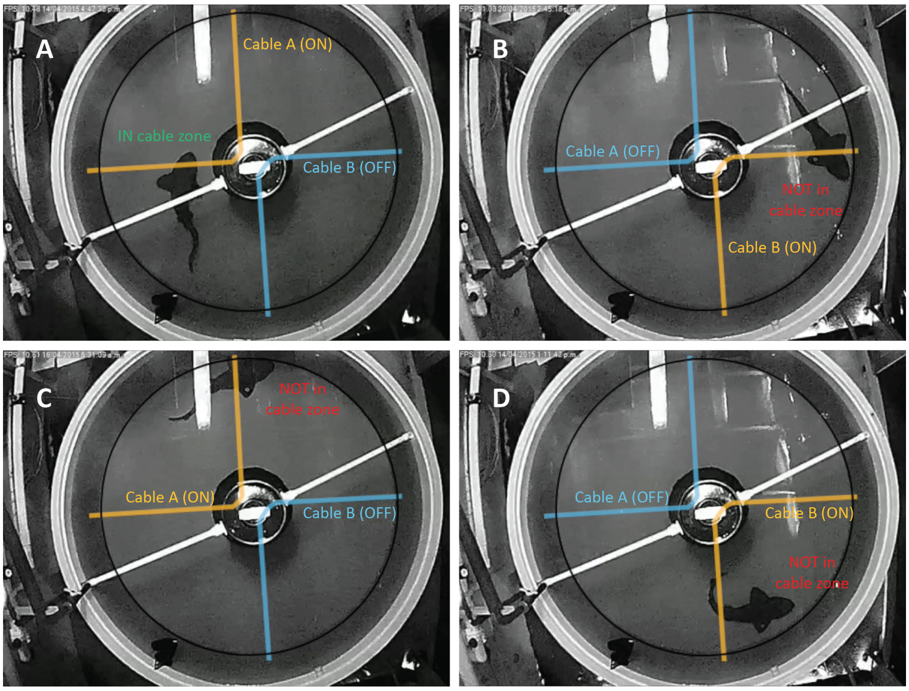


Figure 4.3 – Stills of video footage from several different experiments showing examples of when the shark was considered to be in the cable zone (still A) and not or no longer in the cable zone (stills B, C and D). The yellow cable is the one switched on, and the blue cable is switched off. The shark is considered to be in the cable zone when any part of its head (up to the pectoral fins) was crossing the cable.

Since the ampullae of Lorenzini in sharks are concentrated around the head and mouth area, the animal was considered to encounter or interact with the cable zone as soon as any part of its head (up to the pectoral fins) crossed the cable. Measurement of the shark's distance from the cable was difficult, particularly given that it was not possible to introduce a side-facing camera due to the potentially confounding EMFs that it would introduce into the tank. Examples of what was considered in *vs*. not in the cable zone are shown in Figure 4.3.

4.4 Results

4.4.1 Categorisation of observed behaviours

The three behaviours observed and described for the New Zealand eagle rays (*Myliobatis tenuicaudatus* Hector, 1877) in Chapter Three (refer to Table 3.3) were used as a starting basis for the categorisation of behaviours in these experiments. The three broad categories were adapted to fit the behaviours of carpet sharks observed before and during experimentation. An additional category of "Undirected swimming" was added after this behaviour was unexpectedly observed during experimentation, as shown in Table 4.3.

Table 4.3 – Description of how the various observed and expected behaviours were categorised for analysis

Behaviour	Description & Examples
Repel/Avoid	Animal clearly avoids the cable zone or is repelled by it Animal won't cross the cable zone, either by immediately changing direction or drastically changing position in the water column
Attract/ Investigate	Animal attracted to the cable zone Investigates the cable zone and spends time around it Exhibits "searching" or "foraging" behaviour around cable zone
Undirected swimming	Animal does a vigorous head shake as it swims through the cable zone, swims with no clear direction for a few seconds before resuming normal swimming in a set direction
Ignore/Cross	Animal does not respond to/ignores cable zone Animal swims through the cable zone with no visible reaction Animal sits in cable zone with no apparent reaction

4.4.2 Results

As shown in Table 4.4, a total of 526 behavioural interactions were observed and recorded over 72 experiments, of which only six interactions were a response within the cable zone (one undirected swimming response, five avoidance responses). Three of the avoidance responses were to cables with no power running through them. No instances of investigatory behaviour were observed, which is clearly shown in Figure 4.4.

The two observed response behaviours (avoidance and undirected swimming) were grouped together into a "response" category for analysis.

Mann-Whitney U tests were conducted to determine whether there were differences between the sharks' responses to Cable A when it was on and Cable B when it was on, and between Cable A when it was off and Cable B when it was off. No significant differences were found ($p > 0.1$ in all cases) and so the behavioural response data for experiments with one of the cables switched on were pooled into "ON cable" and "OFF cable" (see Table 4.4). Similarly, the data for controls, when both the cables were switched off were also pooled. This was done to simplify further data analysis.

Table 4.4 – Overview of total number of behavioural responses shown within the cable zones across all 526 observed interactions by four individuals over the course of 72 experiments. Power ON indicates an experiment in which either Cable A or Cable B was switched on, and the controls were where both cables were switched off during the experiment.

	No olfactory stimulus			Olfactory stimulus		
	Experiment with power ON		Control	Experiment with power ON		Control
Behavioural response	ON cable	OFF cable	OFF cables	ON cable	OFF cable	OFF cables
Cross (no response)	62	56	71	106	93	132
Avoid	1	0	2	1	1	0
Investigate	0	0	0	0	0	0
Undirected swimming	0	0	0	1	0	0
Total	**63**	**56**	**73**	**108**	**94**	**132**

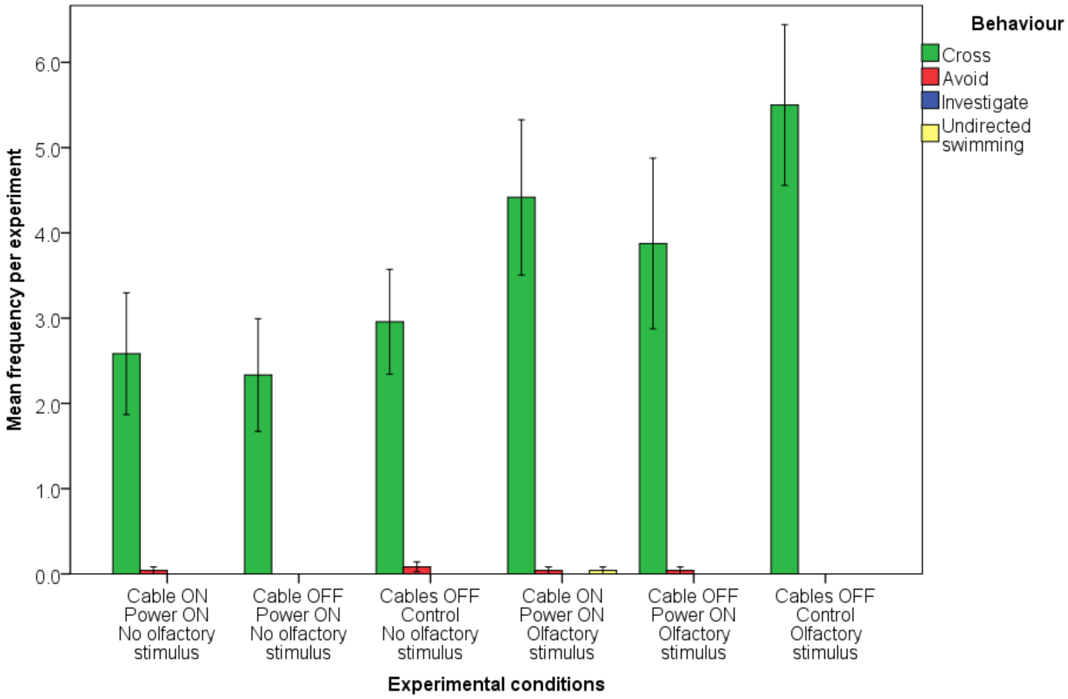


Figure 4.4 – Mean frequency (± 1 standard error) of each behavioural response (cross, avoid, investigate or undirected swimming) in the cable zones across each experimental treatment (including controls with no power through either cable). The data are from four individual sharks across a total of 72 experiments. Cable OFF Power ON refers to the control (switched-off) cable during experiments where the power is switched on.

The sharks showed significantly more non-responses (crossing) to the cable zones than responses (avoidance or undirected swimming), as evidenced by the Wilcoxon Signed Ranks tests shown in Table 4.5, showing that the sharks crossing the cable was the norm, both when the sharks were foraging (prompted by the addition of an olfactory stimulus) and not. Whether the cable was switched on or off made no significant difference to the frequencies of either response or non-response to the cable zones, regardless of whether the sharks were foraging or not, indicating that the sharks' normal behavioural responses were not altered by the presence of EMFs around the cable.

Kruskal-Wallis tests were conducted to determine whether the distribution of behavioural response and non-response data were affected by the addition of an olfactory stimulus. As shown in Table 4.6, no significant differences ($p > 0.05$, df = 3 in all cases) in behavioural response were found, indicating that the sharks either responded to or crossed the cable zones in similar frequencies regardless of whether they were foraging or not.

Table 4.5 – Analysis of differences in response (avoid & undirected swimming pooled) and non-response (cross) to the two different cables within four different experimental treatments (including control treatments), showing the Wilcoxon Signed Ranks Z statistic and statistical significance (*p*) for each pair being compared. ^{A} denotes a Z statistic based on positive ranks, ^{B} based on negative ranks, * denotes statistical significance at the level $p < 0.05$, ** at the level $p \leq 0.01$, *** at the level $p \leq 0.001$

Treatment	Differences	Z	*p*
No olfactory stimulus, Power ON	ON cable response *vs.* ON cable no response	-3.19 ^{A}	**0.001*** **
	OFF cable response *vs.* OFF cable no response	-3.20 ^{A}	**0.001*** **
	ON cable response *vs.* OFF cable response	-0.09 ^{B}	0.93
	ON cable no response *vs.* OFF cable no response	-1.00 ^{B}	0.32
No olfactory stimulus, Power OFF	OFF cables response *vs.* OFF cables no response	-3.74 ^{A}	**<0.001*** **
Olfactory stimulus, Power ON	ON cable response *vs.* ON cable no response	-3.73 ^{A}	**<0.001*** **
	OFF cable response *vs.* OFF cable no response	-3.42 ^{A}	**0.001*** **
	ON cable response *vs.* OFF cable response	-1.50 ^{B}	0.13
	ON cable no response *vs.* OFF cable no response	-0.58 ^{B}	0.56
Olfactory stimulus, Power OFF	OFF cables response *vs.* OFF cables no response	-3.93 ^{A}	**<0.001*** **

Table 4.6 – Analysis of differences in distribution of each behavioural response within the two cable zones to the four different treatments (no olfactory stimulus + power on; no olfactory stimulus + power off; olfactory stimulus + power on; olfactory stimulus + power off), showing the Kruskal-Wallis *H* statistic, degrees of freedom (df) and statistical significance (*p*). The 'avoid' and 'undirected swimming' responses were pooled together.

Response	*H*	df	*p*
Cable ON no response (cross)	7.40	3	0.06
Cable ON response (avoid & undirected swimming)	0.70	3	0.87
Cable OFF no response (cross)	7.67	3	0.05
Cable OFF response (avoid & undirected swimming)	2.07	3	0.56

4.5 Discussion

It is clear from the data, as presented in Table 4.4 and Figure 4.4, that the carpet sharks did not respond to the EMFs induced around the power cables. Indeed, the sharks crossed the active cable (the one that was switched on) 98.2% of the time, and across all experiments (including controls with no power on), crossed the cable 98.8% of the time. This is borne out by the highly statistically-significant differences between the frequency of non-response versus the frequency of response exhibited by the sharks, which indicate that the sharks crossed the cable significantly more often than they showed a response of avoidance or undirected swimming. This was the case within each of the treatments, so there was no difference in the lack of behavioural response whether the cables were switched on or off, nor whether an olfactory stimulus was introduced or not.

When comparing the behavioural response data between the different treatments, no statistically-significant differences were found. This means that no difference was observed between experiments with power running through one of the cables and control experiments with no power running through either of the cables. The introduction of an olfactory stimulus did incite a foraging response in the sharks, however, no difference was found in the behavioural response data between experiments (including controls) with versus without olfactory stimuli. This indicates that whilst the sharks were foraging, they did not show any increased interest in the EMFs induced around the cables.

Of the six observed behavioural interactions that were classed as a response, three were avoidance responses to cables with no power running through them, which suggest false positives, where the shark decided to change swimming direction when it happened to be in the cable zone, rather than because it was in the cable zone. Sudden changes in swimming direction were regularly observed, so this was not an unusual occurrence. Whilst it is possible that the sharks did not show a behavioural response to the EMFs because they could not detect them, the one observed instance of an undirected swimming response provides evidence that the sharks did actually detect the EMFs. This undirected swimming response was never observed in any other situation before or after experimentation, which suggests that it was a direct response to the EMFs in the cable zone. However, the single occurrence of this behaviour across all experiments makes it impossible and imprudent to interpret further. It is worth acknowledging that the complete reversal of the experimental animals' circadian rhythm, to enable experimentation to take place during daytime hours (see Section 4.3.2), may have had an unforeseen effect on the animals' behaviour. However, the holding tank and experimental tank were both in the same night/day-reversed room to maximise acclimatisation time to the reversed circadian cycle and minimise any effects. The shark that showed the single undirected swimming response had spent over a month in the holding tank before experiments began.

Although three aversive responses were observed towards active cables (two avoidance and one undirected swimming responses), not a single investigatory response was observed, suggesting that 50 Hz cables are highly unlikely to distract benthic elasmobranchs by acting as phantom prey. In terms of effects and, ultimately, impacts, aversive responses are more concerning compared to investigatory ones, however the very low number of aversive responses (only 1.8% of behavioural interactions with the active cables were aversive responses) and complete lack of investigatory responses demonstrate that effects of submarine AC power cables are limited and not cause for concern.

As discussed in the introduction to this chapter and shown in Figure 4.1, round stingrays and thornback guitarfish show peak responses around 2 and 4 Hz, respectively, suggesting that their response sensitivity would be low around 50 Hz, however this requires verifying (Montgomery & Bodznick, 1999). Given the very limited responses of the sharks towards the EMFs around the cables demonstrated in this chapter, it is highly likely that this is the case. Furthermore, in early studies investigating elasmobranch responses to various fields by eliciting rhythmic spiracle valve movements in thornback skates (*Raja clavata* Linnaeus, 1758) and eye-blink reflexes in lesser-spotted dogfish (*Scyliorhinus canicula* Linnaeus, 1758), 50 Hz fields were described as “ineffective” suggesting very low or perhaps even no responses, although further details were not given (Kalmijn, 1988).

4.5.1 Expected impacts of submarine AC power cables on elasmobranchs

It is clear that submarine AC power cables do not seriously affect the behaviour of benthic elasmobranchs at the frequencies currently in use in New Zealand (50 Hz) and globally (50 to 60 Hz). This is likely largely due to the low response sensitivity of the elasmobranch electrosensory system at such frequencies. However the single observed instance of undirected swimming behaviour in the experimental cable zone does suggest that behavioural responses may occur occasionally, though are unlikely to be long-lasting, and are certainly not expected to translate into any kind of discernible impacts.

CHAPTER FIVE:

THE IMPACTS OF SUBMARINE DIRECT CURRENT POWER CABLES ON BENTHIC SHARKS

5.1 Abstract

Direct current (DC) power cables are more efficient for energy transmission over long distances and are thus often a preferred option for submarine power cables. The electromagnetic fields (EMFs) generated around submarine DC cables fall within the detection range of the extremely sensitive elasmobranch electrosensory system, which is particularly attuned to DC fields, and consequently, behavioural impacts are a concern. The effects of DC power cables on New Zealand carpet sharks (*Cephaloscyllium isabellum* Bonnaterre, 1788) were studied in the laboratory using EMFs equivalent to those around a 198 A DC submarine power cable in perpendicular 0.10 m s^{-1} seawater flow. The sharks investigated the cables significantly more often when the power was switched on. However, the sharks crossed the active cables 90.9% of the time, and only investigated them 8.1% of the time, showing that crossing the cable was clearly the dominant behaviour. Whilst these DC cables did have a small effect on this species, this is not expected to translate into an impact on benthic elasmobranchs.

5.2 Introduction

5.2.1 Use of submarine DC power cables

As discussed in Chapter Two, power cables are either direct current (DC), where the polarity of the electrical current remains constant, or alternating current (AC), where the polarity constantly alternates at a specific frequency. This chapter is concerned with impacts of DC submarine power cables on the behaviour of benthic elasmobranchs.

DC cables are generally a more cost-effective choice for transporting electricity over long distances, as they can transport more power than a similarly-rated AC cable due to their constant polarity and have lower losses over distance (Chow*, et al.*, 2003; Radi & Rasmussen, 2013). Consequently, DC cables are predominantly used for the transfer of electricity, for example from offshore renewable energy developments (OREDs) that are further than around 30 km from land or across water bodies, such as the HVDC Inter-Islander Link which crosses the Cook Straight in New Zealand (Gill*, et al.*, 2014; Transpower, 2014).

5.2.2 The elasmobranch electrosensory system

Elasmobranchs have demonstrated behavioural responses to weak electric fields as low as 5 nV cm^{-1}, which, combined with its accuracy, makes their extremely sensitive electrosensory system particularly useful for pinpointing hidden prey and also conspecifics (Kalmijn, 1971, 1982; Tricas*, et al.*, 1995). There is variation in the sensitivity of the electrosensory system across species, which is thought to be related to species' niche (Kajiura*, et al.*, 2010). Benthic species which feed on prey often hidden in sediment have particularly well developed electrosensory systems, and it is likely that nocturnal species or those that live in turbid environments do, too (O'Connell*, et al.*, 2014c).

Weak electric fields in seawater, whether they are produced by animals, the Earth's magnetic field or anthropogenic sources, are detected by the electrosensory system through dedicated pores called ampullae of Lorenzini, shown in Figure 1.2A. In sharks, the ampullae of Lorenzini are generally concentrated around the head and mouth, as shown in Figure 1.2B (Gardiner, *et al.*, 2012). The electrosensory system responds to differences in electrical potential between an internal reference and an external stimulus at the pore opening. This difference in electrical potential is detected across the sensory epithelium of the alveoli located within the ampullae of Lorenzini (Sisneros &

Tricas, 2002). Refer to Section 1.4 for further detail on the morphology of the elasmobranch electrosensory system and its detection of electric fields.

The electric potentials produced by a number of marine species were measured and whilst a few were found to produce weak alternating current (AC) fields, almost all the species tested were found to produce weak direct current (DC) fields, ranging from below 1 µV up to 500 µV depending on the species (Kalmijn, 1972; Haine, *et al.*, 2001). The electric fields associated with bivalves and small crustaceans were measured to be less than 1 µV cm^{-1} at a distance of 1 cm (Haine, *et al.*, 2001). Several elasmobranch species are known to use their electrosensory system to navigate over long distances, using the Earth's DC magnetic field and the corresponding electric fields induced by seawater flows and current passing through it. A number of species, including the round stingray (*Urolophus halleri* Cooper, 1863) have been shown to orient to uniform DC electric fields in tanks (Kalmijn, 1982; Klimley, 1993; Gardiner, *et al.*, 2012). It is also important to note that as an elasmobranch swims through a DC field, it will also generate EMFs since it is electrically-conductive.

Consequently, it is to be expected that the elasmobranch electrosensory system is particularly attuned to the detection of weak DC fields, and thus likely to be more impacted by EMFs around DC cables than those around AC cables, which were not found to present an issue, as demonstrated in Chapter Four.

Benthic elasmobranch species have a more sensitive electrosensory system, often with greater electrosensory pore numbers and lower electric field detection thresholds (Raschi, 1978; Haine, *et al.*, 2001; Tricas, 2001; Jordan, *et al.*, 2009a; Kempster, *et al.*, 2016b). They are also significantly more likely to encounter submarine power cables laid on the seabed, and thus much more likely to be impacted by the weak electromagnetic fields (EMFs) induced around such cables in seawater.

5.2.3 Potential impacts of submarine DC power cables on elasmobranchs

The EMFs induced around many submarine power cables fall within the very sensitive detection range of elasmobranchs (refer to Chapters One and Two), which is particularly attuned to DC fields, and thus the EMFs may have a behavioural impact on benthic species that encounter them. Of particular concern is the potential for the EMFs around DC cables to attract elasmobranchs, or to deter elasmobranchs and prevent them from crossing cable zones.

Research into deterring elasmobranchs, particularly from fishing gear or humans, has long proposed the use of electric fields and permanent magnets to overwhelm the electrosensory system. However, studies have met with varying success, including cases where magnets intended to repel sharks were, in fact, found to attract them (Howard, 2011; O'Connell*, et al.*, 2011, 2014b; Porsmoguer*, et al.*, 2015). Since these systems aim to overwhelm the electrosensory system and cause discomfort to the shark, the electric and magnetic field strengths used are at the upper end of the elasmobranch detection range (Howard, 2011). The EMFs around submarine power cables are several orders of magnitude weaker than those used in deterrent devices, and so are not expected to cause any avoidance behaviours.

In experiments where lesser spotted dogfish (*Scyliorhinus canicula* Linnaeus, 1758) were given a choice between complex bioelectric fields produced by its usual prey and a simple artificially-produced DC field of similar strengths, the sharks did not show any preference in the absence of any visual cues (Kimber*, et al.*, 2011). Since the EMFs induced around submarine power cables generally fall at the lower end of the elasmobranch electrosensory detection range, they may overlap with those produced by prey species, and consequently, foraging benthic elasmobranchs may mistake the EMFs for an indication of prey, particularly in the presence of olfactory cues which would indicate the presence of prey. If this is a common and widespread impact of EMFs around submarine power cables, and consequently, an elasmobranch is unable to forage effectively for prey, that individual's fitness will reduce and its ability to grow or reproduce may be affected. If this is a widespread problem within a population, that population, or even species, could be severely negatively impacted.

5.2.4 Choosing experimental parameters

The proposed specifications for the Kaipara Marine Turbine Generation Project were considered representative of specifications commonly used in OREDs and were used to inform the chosen parameters of these experiments. The Kaipara project's ringmain cables linking the turbines to each other in groups of up to 30 (refer to Section 1.3.1 for further details) were proposed to be rated to 350 A and would lie directly on the seabed. Clearly, 350 A would be the maximum electrical current that would pass through the cables, and was only likely to be generated at maximum seawater velocities, which would only happen during spring tides. In order to test electrical strengths more likely to be encountered by benthic elasmobranchs on a quotidian basis, electrical currents closer to 200 A were tested.

As discussed in Chapter Three, there were serious safety concerns regarding running power cables at the voltages and electrical currents that would be used for power transmission over a short distance within a laboratory setting. These concerns were overcome by using the additive property of magnetic fields. A single 2 × 2.5 mm^2 double-core power cable was looped around the same path multiple times so that the magnetic fields around each loop of the cable combined to approximate the magnetic field that would be generated by a single power transmission cable of the specifications required. This meant that experiments could be run using much lower (and significantly safer) electrical currents whilst still simulating field conditions.

In order to replicate the fields induced around a DC submarine power cable with 200 A running through it, the experimental power cable with 30 A running through it was looped around ten times – whilst this theoretically would replicate a cable of 300 A, some losses in the magnetic field were incurred from the looped cables at the bottom and also due to the thickness of the tank bottom.

5.2.5 EMFs around the chosen experimental parameters

Due to the weak nature of the EMFs induced around submarine power cables, it is difficult to accurately measure such weak fields. However, to ensure that the experimental parameters chosen were, indeed, simulating the fields around a 200 A, the magnetic field generated around the experimental cable set-up was measured using a hall-effects sensor and the typical magnetic flux density was measured to be 3.96×10^{-3} T, though this measurement comes with a large error of margin, and the upper and lower bounds of error were 5.55×10^{-3} T and 3.17×10^{-3} T, respectively. Measurements were taken on the tank bottom directly above the cable, and the tank was measured to be 10 mm thick, and not found to impede the magnetic fields.

The above magnetic fields would correspond to those around a cable of 198 A, with upper and lower bounds of 278 A and 159 A, respectively. Whilst the fields cannot be measured extremely accurately, they fall within the range required. Table 5.1 shows the electric field strengths expected to be induced by a seawater flow perpendicular to the DC cables with a velocity of 0.10 m s^{-1}, based on the above measurement of a typical magnetic flux density of 1.43×10^{-3} T and the measurements taken of the seawater velocity throughout the experimental tank.

Table 5.1 – Electric field (EF) strengths around the experimental DC power cable expected to be induced by seawater flowing at a velocity of 0.10 m s^{-1} perpendicular to the cable and at several distances from the cable. EFs were calculated using Equations 2.1 and 2.3 and measures of a typical magnetic field of 3.96×10^{-3} T induced by the DC cable in the experimental tank. If cable is resting on the seabed, 0° is perpendicular to the seabed (directly above cable) and 90° is parallel to the seabed. Burying or half-burying the cable does not affect the EMF strengths.

Distance from cable (m)	**Angle from seabed**	**Induced EF strength (nV cm^{-1})**
0.01	0° (⊥ to seabed)	3960.0
	30°	3429.5
	45°	2800.1
	60°	1980.0
	90° (ǁ to seabed)	0.0
0.05	0°	792.0
	30°	685.9
	45°	560.0
	60°	396.0
	90°	0.0
0.10	0°	396.0
	30°	342.9
	45°	280.0
	60°	198.0
	90°	0.0

5.2.6 Study species: New Zealand carpet shark

The New Zealand carpet shark (*Cephaloscyllium isabellum* Bonnaterre, 1788) is a small benthic shark endemic to New Zealand. It is commonly found throughout New Zealand's coastal waters, including the Chatham Islands and Stewart Island. Most individuals are found above 400 m, though they have been caught up to depths of 673 m (Francis, 2003). Its depth range appears to vary around New Zealand and also seasonally, and is likely temperature-driven.

C. isabellum generally inhabits rocky reefs, but is also found in sandy-bottomed habitats. They often move out onto sand flats to forage at night, and are opportunistic predators, feeding on fish, crustaceans and small cephalopods (Cox & Francis, 1997; Francis, 2012). Refer to Section 4.2.6 for further information about this species.

Since carpet sharks are nocturnally-active and opportunistic, they are likely to rely on their electrosensory system to detect or pinpoint prey, as discussed in Section 4.2.6. As benthic elasmobranchs, they are also relatively likely to encounter submarine power cables, especially given their wide distribution throughout New Zealand. These sharks are a good laboratory species as they acclimatise to new tanks and laboratory environments quickly, rapidly return to normal behaviour after handling and do not appear unduly stressed by captivity. Consequently, their behaviour in tanks is likely to reflect their natural behaviour.

5.3 Methods

5.3.1 Study animals

The carpet sharks used in these experiments were caught and housed under University of Auckland Ethics Approval number 001284.

All of the animals were caught as by-catch in the cray-pots of local cray fishermen working out of Leigh harbour in October and November 2013 (see Table 5.2). Animals were landed at Leigh wharf by the fishermen, whence they were collected and transported to the Leigh Marine Laboratory in lidded transportation tanks filled with seawater. The sharks were then transferred to a large holding tank to acclimatise to laboratory conditions.

Table 5.2 – Details of the six New Zealand carpet sharks caught for the experiments presented in this chapter, including sex, nose-to-tail length, date caught and method used to catch them. The locations are as reported by the fishermen who caught the animals.

Animal	Sex	Length (m)	Date caught	Location caught	Catch method
CS1: Glenfiddich	M	0.59	04-10-2013	Great Barrier Island	Cray-pot by-catch
CS2: Aberlour	F	0.71	04-10-2013	Great Barrier Island	Cray-pot by-catch
CS3: Balvenie	F	0.63	04-10-2013	Great Barrier Island	Cray-pot by-catch
CS4: Glenlivet	F	0.66	04-10-2013	Great Barrier Island	Cray-pot by-catch
CS5: Cragganmore	M	0.63	05-11-2013	Takatu	Cray-pot by-catch
CS6: Spotty Hat	F	0.72	05-11-2013	Takatu	Cray-pot by-catch

On arrival, each shark was tagged to easily differentiate individuals in the holding tank. The tags were made of white PVC or black polyethylene in different shapes and were sized appropriately to the sharks. A hole was made through one of the sharks' pectoral fins using a sterilised leather hole-puncher, and the tag fitted through and fixed with a sterilised plastic bolt and nut. The healing of the hole was monitored and no infection ever occurred. The tags were easily removed by unblocking the nut once individual identification was no longer required (after experimentation), and the remaining hole rapidly healed over.

The sharks were considered acclimatised to the laboratory environment once they were feeding consistently and showed no other signs of stress. All animals acclimatised within ten days of arriving at the laboratory. Experiments were only run if animals were feeing consistently, as loss of appetite can be indicative of stress (Charbeneau, 2004).

No territoriality or fighting was observed between the sharks, so when not in the experimental tank, the animals were kept together in the same holding tank, a large circular tank of 2 m in diameter and 1.5 m water depth.

There was a continuous flow of seawater through the holding tank, and two air stones provided additional aeration of the water.

The seawater to both the holding and experimental tanks was cooled to 18°C or below during summer and early autumn, as the sharks were observed to show signs of heat stress at water temperatures above 19°C. Ambient seawater temperature over the rest of the year was lower than 18°C, and thus didn't require cooling.

The sharks were fed chopped-up pilchard to maximise the effectiveness of using ground pilchard as an olfactory stimulus. They were occasionally fed mussels and squid for variety. They were fed twice per week.

5.3.2 Experimental tank set-up

The experimental tank was circular, with a diameter of 2 m and a water depth of 0.55 m, and a circular plinth in the middle of the tank. Both the tank and the plinth were made of plastic to avoid interactions between the tank and the EMFs. A camera was suspended above the centre of the tank to record all experiments, and in order to maximise the contrast between the shark and the tank on the video footage, the tank was white.

Cephaloscyllium isabellum is nocturnal, so the experimental tank was set up in a room with a reversed night/day cycle so that experiments could be run when the sharks are most active. To enable us to see whilst running the experiments and to allow the camera to film, a red light was on during the day. The camera was also fitted with infra-red lights to further aid filming. Normal white lights came on during the night to simulate daylight. Since abrupt transitions between "day" and "night" have been known to cause undue stress to animals in captivity, and consequent strange behavioural responses, dusk and dawn were also simulated (Charbeneau, 2004; Choromanski, 2004). The holding tank was in the same room, to minimise the unforeseen behavioural effects of the circadian rhythm reversal, as discussed in Chapter Four.

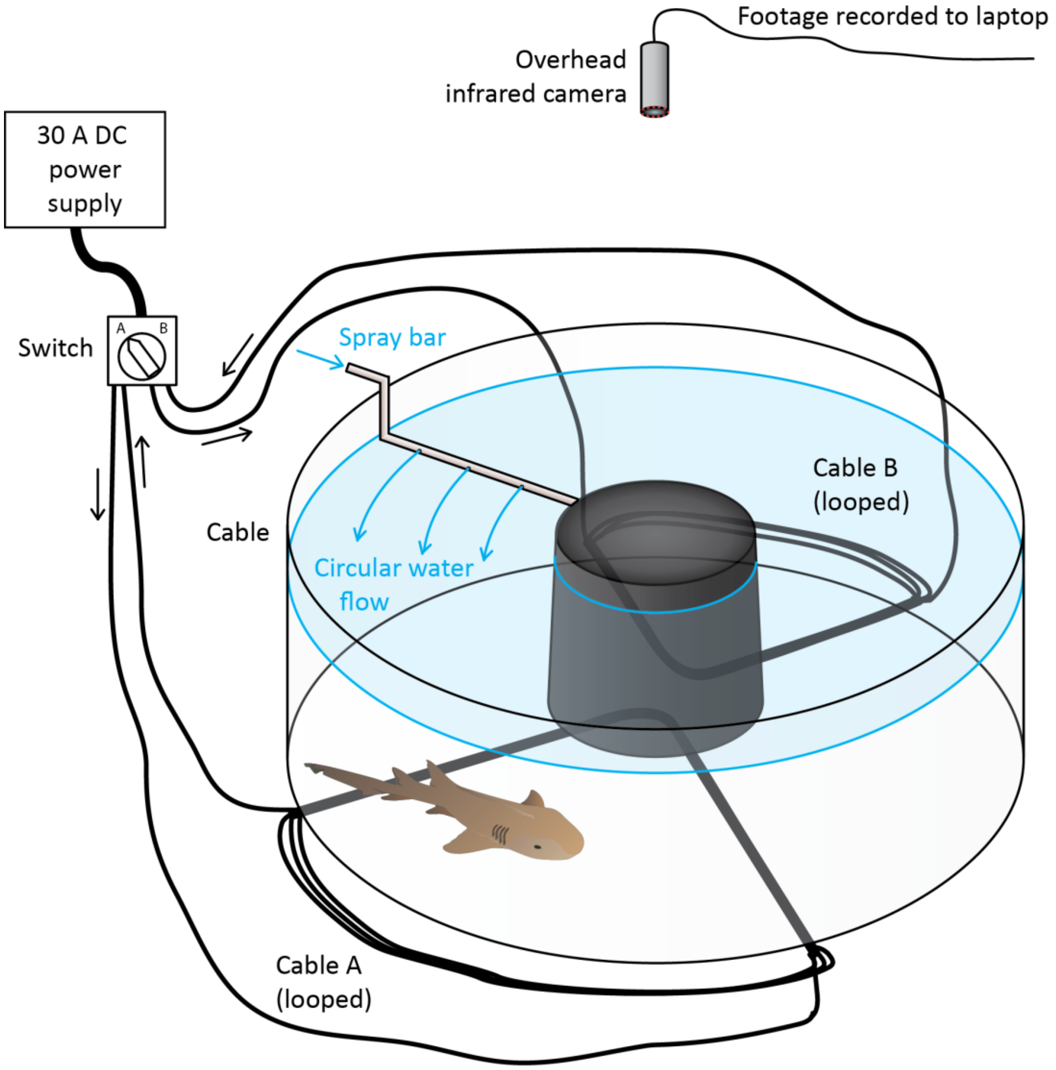


Figure 5.1 – Diagram of the experimental tank set-up, showing the two separate cables (A and B) underneath the tank, each looped around ten times to increase the strength of the magnetic field generated around them. Power to one of the cables is delivered from a DC power source – both cables cannot be switched on at the same time. A constant circular seawater flow around the tank is maintained throughout experiments.

As shown in Figure 5.1, two separate cables were laid directly underneath the tank, but both connected to the same power supply such that only one or neither of the cables can be switched on at any given time. The Powertech MP3094 switching mode power supply was set up to deliver a constant DC current of 29.8 A through the connected cable (A or B).

A constant anti-clockwise circular water flow was maintained by having water flow in through a spray bar with angled holes, and the out flow was located in the centre of the bottom of the tank. This ensured that the seawater crossed the cables as perpendicularly as possible.

5.3.3 Experimental protocol

Experiments were conducted on each carpet shark individually. Animals were given at least one week to acclimatise to the experimental tank before experiments began. Loss or lack of appetite is a common indicator of stress, so animals were considered acclimatised once they had fed for at least two consecutive feedings, unless any abnormal behaviours were observed.

Each experiment lasted 20 minutes, determined by the length of time over which the power supply could be run safely in a tank-room environment whilst also maximising the likelihood of the experimental animal encountering the EMFs around the cable. The power supply was controlled manually, and all experiments were timed – an experiment started when the power supply was switched on, and ended when the power supply was switched off. No experiments were terminated early due to signs of distress from the shark.

Control experiments, where no electrical current was running through either cable, were also 20 minutes and followed the same procedure as experiments with power.

All experiments were observed in person and also recorded using an overhead camera with infra-red capabilities to enable the experiments to be filmed under night-simulating red light. The footage was recorded and saved to a laptop using iSpy v6.0.0.0 software. Any behaviours of interest observed directly during experimentation were noted.

A maximum of three experiments were conducted per day, with a resting time of at least 2.5 hours between each experiment. On experimental days one experiment was run with Cable A switched on, one with Cable B switched on and one control (neither cable switched on). The order of experiments was randomised so that the order of experiments varied from day to day.

The experimental tank's air stone was removed during experiments as the bubbles created too much turbulence and reflection on the water surface and interfered with the clear filming of the experiments. During the temporary removal of the air stones, the experimental tank's oxygen levels were kept at satisfactory levels by the constant seawater inflow into the tank.

In order to investigate whether the sharks responded differently to the induced EMFs around a cable when foraging versus normal behaviour, some of the experiments were conducted with the addition of an olfactory stimulus.

5.3.4 Olfactory stimuli

One pilchard was defrosted in fresh water for 30 minutes and then blended in a food processor with enough of the defrosting water to create a liquid. For each experiment, 20 ml of this blended pilchard water was used an olfactory stimulus. The olfactory stimulus was introduced into the tank using a syringe at the start of the experiment at the same time as the power supply was switched on, or, in the case of a control, at the start of the experiment. The circular water flow ensured that the olfactory stimulus was quickly distributed throughout the tank and water column.

During preliminary testing of possible olfactory stimuli, animals showed a good response to blended pilchard with a distinct change in behaviour and clear searching pattern around the bottom of the tank, indicative of foraging. Over time, the response of certain individuals reduced. Other olfactory stimuli were tested, but did not incite stronger foraging responses. Starving the animals prior to olfactory experiments also did not have an effect, and was not pursued, since it was considered likely to just cause unnecessary stress to the animals.

5.3.5 Categorisation of behaviours and analysis of results

The experimental animals were observed across a range of situations (including whilst in the holding tank, after being moved to a new tank, whilst foraging and whilst feeding), and all observed behaviours were noted and categorised. This also formed a basis for determining "normal" behaviours when monitoring the sharks' general health. During experimentation, the observation of the sharks in real time allowed for any new behaviours to be immediately added to the behavioural classification table.

Post-experiment, the recorded videos of each experiment were watched and the behaviour exhibited by the experimental animal in each interaction with the cable zones was categorised as one of the three behaviours described in Table 5.3. The experiments were divided into four 5-minute segments, and the frequency that each behaviour occurred in each segment of each experiment was recorded.

In sharks, the ampullae of Lorenzini are concentrated around the head and mouth area, so the animal was considered to encounter or interact with the cable zone as soon as any part of its head (up to the pectoral fins) crossed the cable. The limitations and constraints of this method are discussed in Section 4.3.5. Examples of what was considered being in versus not in the cable zone are shown in Figure 4.3.

5.4 Results

5.4.1 Categorisation of observed behaviours

The three broad behavioural categories (avoidance, attraction and crossing the cable) observed in the pilot experiments conducted with the New Zealand eagle rays (*Myliobatis tenuicaudatus* Hector, 1877) in Chapter Three (please refer to Table 3.3) were used as a starting point for the categorisation of behaviours in these experiments. The categories were adapted to fit the behaviours of the carpet sharks observed before, during and after experimentation, as described in Table 5.3. There were no instances of the undirected swimming response observed in one of the sharks in Chapter Four (please refer to Table 4.2).

Table 5.3 – Description of how the various observed and expected behaviours were categorised for analysis.

Behaviour	Description & Examples
Repel/Avoid	Animal clearly avoids the cable zone or is repelled by it Animal won't cross the cable zone, either by immediately changing direction or drastically changing position in the water column
Attract	Animal attracted to the cable zone Investigates the cable zone and spends time around it Exhibits "searching" or "foraging" behaviour around cable zone
Ignore/Cross	Animal does not respond to/ignores cable zone Animal swims through the cable zone with no visible reaction Animal sits in cable zone with no apparent reaction

5.4.2 Results

To determine whether responses to experiments conducted with Cable A switched on and experiments conducted with Cable B switched on could be pooled together, Mann-Whitney U tests were conducted. No significant differences were found ($p > 0.2$ in all cases) and so the response data for whichever cable was switched on were pooled together ("ON cable" in Table 5.4), as were the data for whichever cable was switched off ("OFF cable" in Table 5.4). The data from the two cables in the control experiments were also pooled. This was done to both simplify the data analyses and increase their robustness.

Over the course of 264 experiments, a total of 1221 behavioural interactions with the cable zones were recorded. Of these interactions, a total of 48 involved a response – 37 were investigatory responses and 11 were avoidance responses. As shown in Table 5.4, seven of the avoidance responses were shown to cables with no power running through them, suggesting that what looked like an avoidance response (the animal suddenly changed direction to avoid the cable zone) was likely to have just been the animal randomly changing direction as it was swimming (this has been observed as a normal behaviour) just as it happened to encounter the cable zone.

Table 5.4 – Overview of the total number of behavioural responses shown within the cable zones across all 1221 observed interactions by six individual sharks over the course of 264 experiments. Power ON indicates an experiment in which either Cable A or Cable B was switched on, and Power OFF indicates either the cable switched off during an experiment or both cables during a control experiment (during which both cables were switched off).

	No olfactory stimulus			Olfactory stimulus		
	Power ON to either cable		Control	Power ON to either cable		Control
Behavioural response	ON cable	OFF cable	OFF cables	ON cable	OFF cable	OFF cables
Cross (no response)	112	106	83	279	282	311
Avoid	2	0	0	2	5	2
Investigate	10	0	0	25	1	1
Total	**124**	**106**	**83**	**306**	**288**	**314**
Number of experiments	49	49	46	40	40	40

The mean frequencies of each response behaviour per experiment are shown in Figure 5.2, showing a clear higher overall mean frequency of behavioural encounters with the cable zone during experiments with an olfactory stimulus. It is also clear that the predominant behaviour in all experiments (whether the power is on or off, and whether an olfactory stimulus is added or not) is that the sharks crossed the cable. A few avoidance responses were observed but they appear to be random due to their occurrence around cables that were switched off, and occurred more often in experiments with the introduction of an olfactory stimulus. It is also clear that there were a number of investigation responses and that they primarily occurred when the cable was switched on, both in experiments with and without an olfactory stimulus. Only two observed instances of investigation were observed towards the switched-off cable, as shown in Table 5.4.

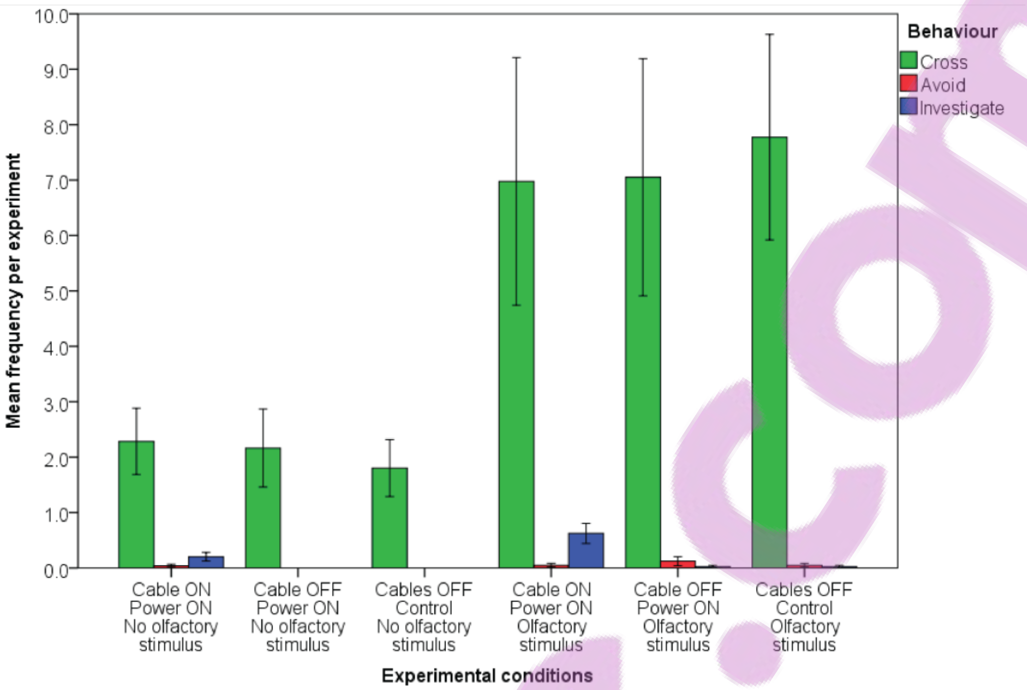


Figure 5.2 – Mean frequency (± 1 standard error) per experiment of each behavioural response (cross, avoid or investigate) in the cable zones across each experimental treatment (including controls with no power through either cable). The data are from six individual sharks across a total of 264 experiments.

Wilcoxon Signed Ranks tests were run to detect differences between the frequencies of the different behavioural responses (investigate, avoid and cross) to the cable zones within each treatment. As shown in Tables 5.5 and 5.6, significantly more non-responses (crossing) than both investigation and avoidance responses were shown in all treatments, whether the cable was on or off, and whether there was an olfactory stimulus or not ($p < 0.001$ in all cases). No differences were found between the frequencies of sharks both crossing and avoiding the cable that was switched on and the cable that was switched off. However, significantly more investigatory responses to the cable that was switched on than the cable that was switched off were observed ($p = 0.015$ in experiments with no olfactory stimulus, $p = 0.003$ in experiments with an olfactory stimulus). In the presence of an olfactory stimulus, significantly more investigatory than avoidance responses were shown towards the cable that was switched on ($p = 0.004$), but no significant difference was found between the two responses in any other treatment.

Table 5.5 – Analysis of differences between frequencies of investigatory, avoidance and non-response (crossing) interactions with the cable zones, within experiments and controls (with no power switched on to either cable) with no olfactory stimulus, showing the Wilcoxon Signed Ranks Z statistic and statistical significance (*p*) for each pair being compared. ^{A} denotes a Z statistic based on positive ranks, ^{B} based on negative ranks, ^{C} based on equal ranks (sum of negative ranks and sum of positive ranks are equal), * denotes statistical significance at the level $p < 0.05$, ** at the level $p \leq 0.01$, *** at the level $p \leq 0.001$.

Treatment	**Differences**	***Z***	***p***
No olfactory stimulus, Power ON	ON cable investigate *vs.* ON cable no response	-3.92^{A}	**<0.001*** **
	ON cable avoid *vs.* ON cable no response	-4.21^{A}	**<0.001*** **
	ON cable investigate *vs.* ON cable avoid	-1.90^{B}	0.06
	OFF cable investigate *vs.* OFF cable no response	-3.63^{A}	**<0.001*** **
	OFF cable avoid *vs.* OFF cable no response	-3.63^{A}	**<0.001*** **
	OFF cable investigate *vs.* OFF cable avoid	0.00^{C}	1.00
	ON cable investigate *vs.* OFF cable investigate	-2.43^{B}	**0.015***
	ON cable avoid *vs.* OFF cable avoid	-1.41^{A}	0.16
	ON cable no response *vs.* OFF cable no response	-1.45^{B}	0.15
No olfactory stimulus, Cables OFF (control)	OFF cable investigate *vs.* OFF cable no response	-3.74^{A}	**<0.001*** **
	OFF cable avoid *vs.* OFF cable no response	-3.74^{A}	**<0.001*** **
	OFF cable investigate *vs.* OFF cable avoid	0.00^{C}	1.00

Table 5.6 – Analysis of differences between frequencies of investigatory, avoidance and non-response (crossing) interactions with the cable zones within experiments and controls (with no power switched on to either cable) with the addition of an olfactory stimulus, showing the Wilcoxon Signed Ranks Z statistic and statistical significance (*p*) for each pair being compared. ^{A} denotes a Z statistic based on positive ranks, ^{B} based on negative ranks, ^{C} based on equal ranks (sum of negative ranks and sum of positive ranks are equal), * denotes statistical significance at the level $p < 0.05$, ** at the level $p \leq 0.01$, *** at the level $p \leq 0.001$

Treatment	Differences	*Z*	*p*
Olfactory stimulus, Power ON	ON cable investigate *vs.* ON cable no response	-4.39 ^{A}	**<0.001*** **
	ON cable avoid *vs.* ON cable no response	-4.38 ^{A}	**<0.001*** **
	ON cable investigate *vs.* ON cable avoid	-2.90 ^{B}	**0.004** **
	OFF cable investigate *vs.* OFF cable no response	-4.38 ^{A}	**<0.001*** **
	OFF cable avoid *vs.* OFF cable no response	-4.38 ^{A}	**<0.001*** **
	OFF cable investigate *vs.* OFF cable avoid	1.13 ^{A}	0.26
	ON cable investigate *vs.* OFF cable investigate	-2.97 ^{A}	**0.003** **
	ON cable avoid *vs.* OFF cable avoid	-0.82 ^{A}	0.41
	ON cable no response *vs.* OFF cable no response	-0.92 ^{A}	0.36
Olfactory stimulus, Cables OFF (control)	OFF cable investigate *vs.* OFF cable no response	-4.46 ^{A}	**<0.001*** **
	OFF cable avoid *vs.* OFF cable no response	-4.46 ^{A}	**<0.001*** **
	OFF cable investigate *vs.* OFF cable avoid	-0.58	0.56

Looking at each behavioural response individually, Kruskal-Wallis tests were conducted to test the effects of the different treatments. As shown in Table 5.7, significant differences between treatments were found for investigation to the ON cable and for no response to both the ON cable and OFF cable.

Table 5.7 – Analysis of differences in distribution of each behavioural response to the four different treatments, showing the Kruskal-Wallis *H* statistic, degrees of freedom (df) and statistical significance (p). * denotes statistical significance at the level $p < 0.05$, ** at the level $p \leq 0.01$, *** at the level $p \leq 0.001$

Behavioural response	*H*	df	*p*
ON cable investigation	23.70	3	**<0.001*** **
ON cable avoidance	2.28	3	0.52
ON cable no response (cross)	13.84	3	**0.003** **
OFF cable investigation	2.39	3	0.50
OFF cable avoidance	6.55	3	0.09
OFF cable no response (cross)	18.42	3	**<0.001*** **

Post-hoc Mann-Whitney U comparisons were conducted for the behavioural responses where significant differences were found (as reported in Table 5.7) to ascertain the source of effect, as reported in Table 5.8. Bonferroni corrections ($p < 0.0125 = 0.05/4$) were applied per behavioural response.

Significant differences in the ON cable investigation data were found between the experiments and controls both with ($p = 0.001$) and without ($p = 0.008$) the addition of an olfactory stimulus, indicating a significant difference in response depending on whether the cable was switched on (ON cable investigate experiments) or off (ON cable investigate controls). There was no significant difference when comparing olfactory and non-olfactory experiments, suggesting that response was similar, regardless of whether an olfactory stimulus was introduced or not.

The only significant difference in the ON cable no response data was between olfactory *vs*. non-olfactory controls. Likewise with the OFF cable no response data, the only significant differences were between olfactory and non-olfactory controls, and also between olfactory and non-olfactory experiments.

Table 5.8 – *Post-hoc* analyses of selected treatment effects within the behavioural responses which showed a significant difference in Table 5.7, showing Mann-Whitney U test statistic and statistical significance (*p*). When applying Bonferroni corrections per behavioural response * denotes statistical significance at the level $p < 0.0125 = 0.05/4$, ** at the level $p < 0.0025 = 0.01/4$.

	Comparisons	**U**	***p***
ON cable investigate	Experiment No Olfactory *vs.* Control No Olfactory	966.0	**0.008***
	Experiment Olfactory *vs.* Control Olfactory	576.0	**0.001****
	Experiment No Olfactory *vs.* Experiment Olfactory	811.5	0.05
	Control No Olfactory *vs.* Control Olfactory	897.0	0.28
ON cable no response	Experiment No Olfactory *vs.* Control No Olfactory	1041.5	0.48
	Experiment Olfactory *vs.* Control Olfactory	705.5	0.35
	Experiment No Olfactory *vs.* Experiment Olfactory	769.0	0.07
	Control No Olfactory *vs.* Control Olfactory	574.0	**0.001****
OFF cable no response	Experiment No Olfactory *vs.* Control No Olfactory	1101.5	0.83
	Experiment Olfactory *vs.* Control Olfactory	727.5	0.47
	Experiment No Olfactory *vs.* Experiment Olfactory	669.5	**0.006***
	Control No Olfactory *vs.* Control Olfactory	574.0	**0.001****

5.4.3 Habituation

Since investigatory responses to the cable, both with and without an olfactory stimulus, were shown (see Table 5.8), the question arises as to whether this behavioural response is sustained through the course of the experiment or whether the sharks habituate to the presence of the induced EMFs around the cable.

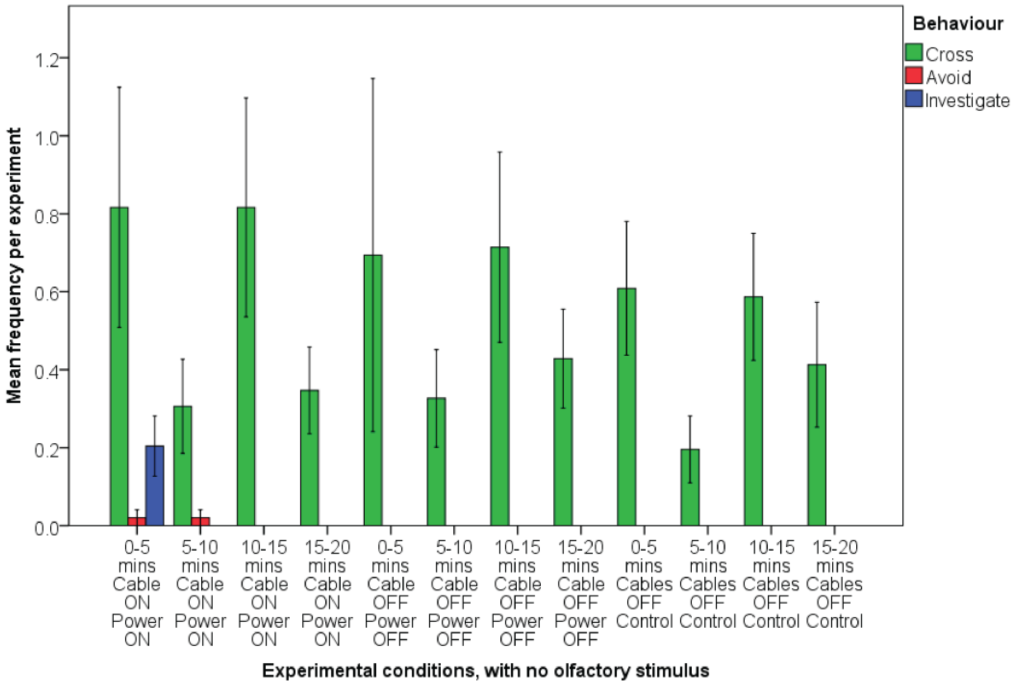


Figure 5.3 – Mean frequency (± 1 standard error) per experiment of each behavioural response (cross, avoid or investigate) observed in the cable zones during experiment and controls with no olfactory stimulus, split into five-minute segments.

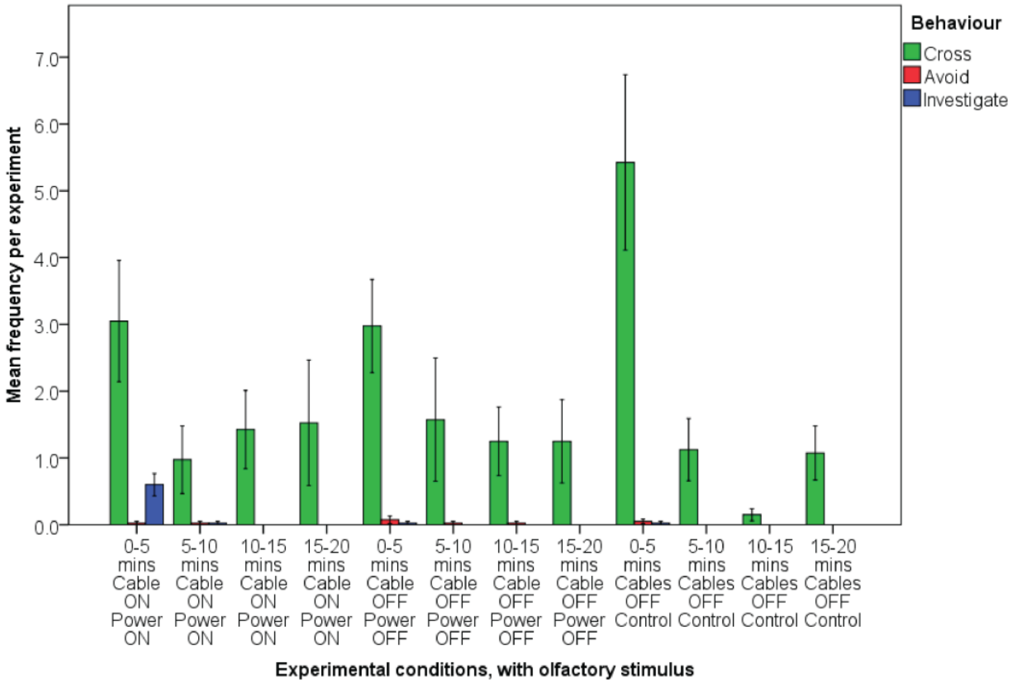


Figure 5.4 – Mean frequency (± 1 standard error) per experiment of each behavioural response (cross, avoid or investigate) observed in the cable zones during experiment and controls with the addition of an olfactory stimulus to incite foraging behaviour, split into five-minute segments.

Each experiment was split into 5-minute segments, and the frequency of behavioural responses (avoid or investigate) observed within the cable zones in each time segment were recorded. Mean frequencies per experiment with no olfactory stimulus are shown in Figure 5.3 and with an olfactory stimulus in Figure 5.4

It is clear from Figures 5.3 and 5.4 that with one exception in an olfactory experiment, all instances of investigation of the cable occurred within the first five minutes of an experiment or control. In the olfactory experiments, the sharks were clearly more active in general in the first five minutes of an experiment after the addition of the olfactory stimulus.

Wilcoxon Signed Ranks tests were then run to compare whether the frequency of investigatory responses changed in frequency over the course of an experiment. As shown in Table 5.9, significantly more investigatory responses were observed within the first five minutes of an experiment than in each of the following 5-minute segments of the experiment. This was found both during olfactory ($p = 0.002$) and non-olfactory experiments ($p = 0.015$). No significant differences were found during control experiments (when cables were switched off).

The same Wilcoxon Signed Ranks tests were conducted on the avoidance response data, but no significant differences in the distribution of avoidance over the different time segments of an experiment (whether the cables were on or off) were found, reflecting the seemingly random occurrences of this behaviour.

Table 5.9 – Analysis of differences in frequencies in sharks' behavioural responses during the first 0-5 mins of an experiment (or control experiment with the cables switched OFF) and responses during 5-10 mins, 10-15 mins and 15-20 mins of the experiment, showing the Wilcoxon Signed Ranks Z statistic and statistical significance (*p*) for each pair being compared. ^{A} denotes a Z statistic based on negative ranks, ^{B} based equal ranks (sum of negative ranks and sum of positive ranks are equal), * denotes statistical significance at the level $p < 0.05$, ** at the level $p < 0.001$

Treatment	Differences	Z	*p*
No olfactory stimulus, Power ON	Investigations in 0-5 mins *vs.* Investigations in 5-10 mins	-2.43^A	**0.015***
	Investigations in 0-5 mins *vs.* Investigations in 10-15 mins	-2.43^A	**0.015****
	Investigations in 0-5 mins *vs.* Investigations in 15-20 mins	-2.43^A	**0.015****
No olfactory stimulus, Cables OFF (control)	Investigations in 0-5 mins *vs.* Investigations in 5-10 mins	0.00^B	1.00
	Investigations in 0-5 mins *vs.* Investigations in 10-15 mins	0.00^B	1.00
	Investigations in 0-5 mins *vs.* Investigations in 15-20 mins	0.00^B	1.00
Olfactory stimulus, Power ON	Investigations in 0-5 mins *vs.* Investigations in 5-10 mins	-3.10^A	**0.002****
	Investigations in 0-5 mins *vs.* Investigations in 10-15 mins	-3.10^A	**0.002****
	Investigations in 0-5 mins *vs.* Investigations in 15-20 mins	-3.10^A	**0.002****
Olfactory stimulus, Cables OFF (control)	Investigations in 0-5 mins *vs.* Investigations in 5-10 mins	-1.00^A	0.32
	Investigations in 0-5 mins *vs.* Investigations in 10-15 mins	-1.00^A	0.32
	Investigations in 0-5 mins *vs.* Investigations in 15-20 mins	-1.00^A	0.32

5.5 Discussion

The sharks showed a clear increase in overall movement within the tank with the introduction of an olfactory stimulus, as expected, indicating that the olfactory stimulus incited more active foraging behaviour. In all experiments and controls, both with and without an olfactory stimulus, the sharks crossed through the cable zones significantly more often than showing a response to the cable zones.

Whilst a few avoidance responses were observed, the responses appeared random and only four out of the 11 total observed cases of avoidance were actually towards the switched-on cable, strongly suggesting that the avoidances were unlikely to be a direct response to the EMFs around the cables.

More instances of investigation than avoidance were observed (37 and 11, respectively), and investigatory responses were predominantly only observed when the cable was switched on, both with and without an olfactory stimulus. These investigatory responses towards the EMFs around the active power cable were statistically significant, showing that they were both detecting and responding to the fields. Through *post-hoc* testing, no significant difference was found between the frequency of investigation when the sharks were foraging (incited by an olfactory stimulus) or not.

No significant differences were found between the sharks' responses and non-responses towards the switched-off cable in an experiment when the other cable was switched off and towards the switched-off cables in a control experiment where both cables were switched off. This indicates that in experiments with one cable switched on, the switched-off cable was a suitable control, and the control experiments with both cables switched off were largely redundant, but necessary as this was not (and could not be) known before the experiments were conducted.

After stratifying the response data into five-minute segments over the course of an experiment, significantly more investigation responses were observed in the first five minutes of an experiment than in any of the other five-minute segments. There was no such significant difference in controls with no power to the cables. No significant difference in avoidance responses through the course of an experiment was found.

5.5.1 Responses to EMFs around DC submarine power cables

It is clear that the sharks were able to cross through the EMFs induced around the power cables – crossing the cable accounted for 96.1% of all 1221 behavioural interactions with the cable zones in all DC experiments, compared to investigatory and avoidance responses which accounted for 3.0% and 0.9%, respectively. When looking solely at responses to the active cables, the sharks crossed the cable 90.9% of the time, whereas they investigated and avoided the active cable 8.1% and 0.9% of the time, respectively. Evidently, and as clearly illustrated in Figure 5.2, although some response behaviours were shown, crossing the cable was the sharks' largely predominant behaviour, both when foraging (incited by the addition of an olfactory stimulus) and not.

This is further supported by the lack of significant difference between the frequency of sharks crossing the cable zones when the cables were switched on compared to when the cables were switched off – switching the cable on has no impact on the sharks' predominant behaviour and they are clearly able to cross through the cable zone without experiencing extreme discomfort.

The few instances of avoidance (11 in total) which made up 0.9% of all behavioural interactions with the cable, and their seemingly random nature, occurring even when the cables were switched off, make it quite clear that DC submarine power cables do not have a repelling effect on benthic sharks. The instances of avoidance occurring when the cables were switched off are likely to be false positives caused by the sharks merely changing direction when in the cable zone and not an active repelling by the EMFs. It is difficult to ascertain whether the avoidances observed towards the cable that was switched on were also false positives, however, given that there were only four such occurrences, fewer than towards the controls, this is not grounds for concern.

However, the significant increase in investigatory response behaviours shown towards the active (switched-on) cable relative to the inactive (switched-off) cable does make it clear that the sharks do detect and occasionally respond to the weak EMFs induced around the cables. This is likely because New Zealand carpet sharks are largely opportunistic foragers, and are thus likely to briefly investigate any EMFs that fall within a range of interest. The electric fields associated with the species' prey are likely to drive the range of interest that would be investigated, and measures of these fields are warranted as current information is limited. Additionally, the hunger level of an individual may affect their response, though this is difficult to quantify accurately beyond the extremes of starvation and satiation. This difference in response was shown both in the Wilcoxon Signed Ranks tests (Tables 5.5 and 5.6), and also in the more specific *post-hoc* Mann-Whitney U analyses (Table 5.8) that were conducted after it was shown that treatments affected investigatory response (Table 5.7).

More investigatory behavioural responses to the cable zones were observed in the presence of an olfactory stimulus compared with no olfactory stimulus (27 and 10 total, respectively), which was expected, given that the sharks are much more active when foraging (and thus, at the very least, more likely to encounter the cable zones). However this difference was not statistically significant, which is likely due to the overall low frequency of investigatory responses during experiments, reducing statistical power during analyses.

The lack of difference between the sharks' behavioural responses to the cable that was switched off during experiments (where the other cable was switched on) and to the cables during controls (where both cables were switched off) indicate that the presence of an active cable did not affect the sharks' behaviour over a large area. Consequently, even if a submarine power cable does have a small behavioural effect on benthic sharks, such an effect will not extend over a distance beyond tens of centimetres from the cable (based on the rapid attenuation of the EMFs over distance), and the shark simply has to move away from the cable zone for any effects to stop. Given that the weak EMFs induced around submarine power cables attenuate quickly over distance (refer to Chapter Two for further information), this is as expected. This would also suggest that burying a cable would also negate most potential effects, although this is not necessarily practical, depending on the benthic substrate, nor economical (CEL, 2006).

The significant difference in non-response behaviours found between the olfactory controls and non-olfactory controls is likely due to the increased activity during foraging, incited by the introduction of an olfactory stimulus. The difference is likely to have been skewed by two olfactory controls during which the experimental sharks were particularly active and crossed through the cable zones at least 40 times.

5.5.2 Habituation to EMFs around DC submarine power cables

It is quite clear from Figure 5.4 that sharks were overall more active in the first five minutes of an experiment or control with the presence of an olfactory stimulus. This spike in activity was not observed in experiments and controls without an olfactory stimulus (Figure 5.3) and was likely prompted by the introduction of the olfactory stimulus at the start of the experiment, which generally incited a near-immediate foraging behavioural response, which then died down over the course of the experiment.

When the sharks' behavioural response data were split into time categories over the progression of the experiment, the clear significant decrease in investigation of an active cable between the first five minutes of an experiment compared to all subsequent time segments (see Table 5.9) indicates that the sharks are likely habituating to the presence of the weak EMFs around the active cable. This is supported by the lack of difference of investigatory response across time segments during controls (with no active cables), although there were significantly fewer responses to compare, and consequently this could be a statistical artefact.

It is also possible that the sharks could be learning that the EMFs they are detecting do not correspond to food. Associative conditioned learning, predominantly using food rewards, has been demonstrated in a number of species, including Port Jackson sharks (*Heterodontus portusjacksoni* Meyer, 1793) which showed association retention rates ranging from 24 hours to potentially 40 days (Guttridge*, et al.*, 2009; Guttridge & Brown, 2014). Habituation to auditory stimuli has also been demonstrated in a number of different shark species (Guttridge*, et al.*, 2009). Experiments have also been conducted demonstrating that juvenile ocellate river stingrays (*Potamotrygon motoro* Müller & Henle, 1841) construct and use spatial maps to help them navigate towards learnt food locations (Schluessel & Bleckmann, 2005). The combination of learning, habituation and potential construction of spatial maps for foraging could enable benthic elasmobranch species to learn where non-prey EMFs, such as those around cables, are located and avoid foraging in those areas.

Whilst New Zealand carpet sharks did appear to habituate to the artificial EMFs or learn that they were not produced by an accessible food source over the course of an experiment, this did not appear to impact their responses in subsequent experiments on the same day nor on subsequent days, suggesting short-term habituation or learning in this particular case. It is unclear whether this is reflective of the cognitive abilities of the experimental species or the experimental design, such as the lack of defining features or landmarks within the experimental tank for the sharks to orient themselves to, however, based on personal observations and anecdotal evidence from local fishermen, the former seems more likely.

If cables were to be laid through the habitat of a largely non-migratory population and were permanently active, such that EMFs were constantly induced around the cables (although strength would likely fluctuate as a function of seawater flow and electrical current through the cables), and consequently the sharks encountered the EMFs more often, it is possible that the habituation would be longer term.

However, the sharks' interest in investigating the cable zones was short-lived and so even if long-term habituation to permanent cables did not occur, it is not expected for the EMFs induced around such cables to be more than a brief short-term distraction for the sharks.

5.5.3 Expected impacts of EMFs around submarine power cables on benthic sharks

Overall, although New Zealand carpet sharks did show some investigation of the EMFs induced around power cables, the predominant behaviour displayed within the cable zones was ignoring or crossing the cables with no apparent discomfort to the sharks. Thus, whilst the cables may have a minimal observed effect, these effects are not likely to cause an overall negative impact, an important distinction (Gill*, et al.*, 2014).

Consequently, it is not expected that DC submarine power cables would have a deleterious impact on benthic shark populations, beyond some initial interest and investigation, particularly in the presence of olfactory cues. However, any short-term interest or impacts are not expected to extend into long-term detrimental impacts, particularly given the rapid habituation to the EMFs shown by New Zealand carpet sharks over the course of a 20-minute experiment. Whilst long-term habituation has not been demonstrated due to experimental design constraints, it is expected that resident animals would either habituate to the EMFs or learn long-term that those particular EMFs are not produced by a potential food source, or, if not, they will habituate or learn over the short-term and any foraging activities will not be majorly impacted.

CHAPTER SIX:

GENERAL DISCUSSION

6.1 Overview

Magnetic fields are generated around submarine power cables by electrical current flowing through the cable. Movement of electrically-conductive seawater through these magnetic fields induces electric fields in the surrounding seawater. Although very weak, these electromagnetic fields (EMFs) are generally within the extremely sensitive detection range of the elasmobranch electrosensory system, which is important in foraging and navigation as well as the detection of conspecifics and predators. This raises concerns over the potential behavioural impacts of the increasing numbers of submarine power cables, particularly those associated with the increasing numbers of offshore renewable energy developments (OREDs). Few directed studies have been conducted to study these impacts, despite the need to understand potential impacts for effective legislation and accurate environmental impact assessments (EIAs). This thesis begins to address these concerns through a series of laboratory-based experiments, and acts as a foundation for future studies.

6.2 Effects of submarine power cables on select elasmobranch species

As detailed in Chapter Two, the strength and geometry of the electromagnetic fields (EMFs) found around and in conjunction with submarine power cables are dependent on the specifications of the cable, the strength of the electrical current, velocity and direction of the seawater and, of course, distance from the cable. Despite calls for research into the possible effects of EMFs associated with submarine power cables, few directed studies have been conducted (Gill, 2005; Gill & Kimber, 2005; Normandeau*, et al.*, 2011; Gill*, et al.*, 2014). The Collaborative Offshore Wind Research into the Environment (COWRIE) mesocosm study tracked the movements of three different elasmobranch species within enclosures set-up over submarine AC power cables. Results showed both inter- and intra-specific variation in behavioural responses, but it was clear that certain individuals were detecting and responding to the EMFs around the cables, mostly by moving closer to them (Gill*, et al.*, 2009). Megafauna surveys conducted along the HVAC power cables that relay electricity to Vancouver Island from mainland Canada found equal frequencies of spotted ratfish (*Hydrolagus colliei* Lay & Bennett, 1839) along cable and control transects (six in both cases), suggesting that the cables were not affecting the animals' movements (Dunham*, et al.*, 2015). A few other studies on elasmobranch electrosensory capabilities, while not directly investigating the impacts of submarine power cables, have suggested interpretations of their findings from the viewpoint of elasmobranchs encountering anthropogenic EMFs. Most notably, lesser spotted dogfish (*Scyliorhinus canicula* Linnaeus, 1758) showed no preference between artificially- and biologically-produced DC electric fields in the absence of any other cues, suggesting that they may not be able to differentiate between the two (Kimber*, et al.*, 2011).

We investigated the effects of the EMFs generated around the equivalent of a 50 Hz 75 A alternating current (AC) cable, a 30 amp direct current (DC) cable and a 198 A DC cable. Seawater velocities of 0.10-0.12 m s^{-1} perpendicular to the cables were used except for some of the 30 A DC experiments which were run with no seawater flow. It is impossible to study all possible power cable specifications and situations, so the chosen experimental specifications serve as a foundation to move into more complex specifications and situations in future studies.

6.2.1 Effects of AC submarine power cables

The behavioural effects of EMFs around submarine AC power cables were investigated using New Zealand carpet sharks (*Cephaloscyllium isabellum* Bonnaterre, 1788) as a study species. The overwhelmingly predominant behavioural response shown by the sharks to the cable zones was to cross the active cable, which would have had EMFs associated with it, 98.2% of the time, as described in Chapter Four. This makes it abundantly clear that the effects of this particular configuration of submarine power cable are minimal, at least in these particular conditions and with this study species.

It is difficult to accurately measure the EMFs that are being investigated due to their weak nature, however, the magnetic field was measured to be 1.43×10^{-3} T, which corresponded to that expected to be induced around a cable of 75 A (refer to Section 4.2.5). Whilst this is an approximation given the complex nature of EMFs generated around submarine AC power cables, the measured magnetic field was stronger than those modelled by Normandeau, *et al.* (2011), the maximum of which was around 1.8×10^{-5} T. However the models assumed that the cables were buried, which would reduce the magnetic fields, which makes it difficult to compare. Theoretically, due to the usual configuration of two equal currents running in opposite directions, an AC power cable shouldn't generate magnetic fields due to self-cancellation. However, this is not the case in reality, and AC power cables generally do have EMFs associated with them (Slater*, et al.*, 2010; Normandeau*, et al.*, 2011; Gill*, et al.*, 2014).

Some instances of avoidance were observed, but in fact occurred more often towards the switched-off cables (with no associated EMFs) than to the switched-on cable, suggesting largely random avoidance behaviours probably as a result of the shark merely changing swimming direction in the cable zone. This could suggest that the EMFs, which are difficult to measure accurately given their very weak nature, were much lower than expected and initially measured. Frequency response curves for round stingrays (*Urolophus halleri* Cooper, 1863) and thornback guitarfish (*Platyrhinoidis triseriata* Jordan & Gilbert, 1880) show peak responses between 2 and 4 Hz, and a clear drop in response thereafter, suggesting that sensitivity in the 50 Hz range may be low (Montgomery, 1984b; Tricas*, et al.*, 1995; Montgomery & Bodznick, 1999). Consequently, this could be interpreted as showing that the EMFs around the active cables were not actually perceived by the sharks, thus explaining their general lack of response. However, the one instance of undirected swimming behaviour sparked in the active cable zone means that the sharks detect the EMFs associated with the active cable but in a way that does not typically interfere with their behaviour.

In the COWRIE mesocosm study which looked at the effects of a submarine AC power cable on three different species of elasmobranchs, some of the animals were found to have moved closer to the cable, though this appeared to vary between individuals (Gill*, et al.*, 2009). The mesocosm study used a 100 A cable, whereas the EMFs investigated in Chapter Four were equivalent to a 75 A cable, which suggests that there may be a threshold at which elasmobranchs start showing investigatory behaviours towards the cables that lies between the two specifications. Alternatively, in the mesocosm study, since it was conducted in the field, there may have been additional environmental factors interacting with the EMFs and making them more interesting to the animals.

6.2.2 Effects of DC submarine power cables

Initially, the effects of a 30 A submarine DC power cables was investigated, using New Zealand eagle rays (*Myliobatis tenuicaudatus* Hector, 1877) as a study species, under conditions of both seawater flow and no seawater flow, as described in Chapter Three. The rays' predominant response to the active cable was to cross it, particularly in conditions of no seawater flow – they crossed the active cable 51.8% of the time during experiments with seawater flow, and 85.1% of the time with no seawater flow. In terms of response behaviours, the rays showed both avoidance and investigation, and investigation was by far the more common behaviour of the two, particularly in the seawater flow experiments.

However, both investigation and avoidance were shown to both the active cable and the switched-off cable and control hose, suggesting that responses may not have been prompted by the presence of the EMFs, which would only have been induced around the active cable. Whilst this raises the question of whether the rays were actually detecting the EMFs, the calculated strengths of the electric field induced by seawater moving perpendicularly to a 30 A DC cable at 0.12 m s^{-1} were well within the detection range of the elasmobranch electrosensory system. At 5 cm from the power cable, the induced electric fields would have ranged up to 144.0 nV cm^{-1} on the seabed, or in the experimental case, on the tank floor (refer to Table 3.1 for more values). Such fields are very weak, but elasmobranchs have shown behavioural responses to fields as low as 5 nV cm^{-1}, with some reports suggesting responses down to 1 nV cm^{-1} in certain individuals, so the experimental induced electric fields would definitely be within range (Kalmijn, 1982; Kajiura & Holland, 2002; Kajiura, 2003). Even taking into account the suggestions that the head movements of animals in experiments showing responses to 1 nV cm^{-1} would have actually amplified the detected field to 20 nV cm^{-1}, the induced electric fields are still within the elasmobranchs' detection range (Petracchi & Cercignani, 1998). This is before considering that the animals moving through the magnetic fields would induce additional weak electric fields, since the animals themselves are also electrically-conductive, adding to the fields already produced by the moving seawater. In the experiments with no seawater flow, the induced electric fields would be much lower and largely produced solely by the movement of the animal – this is the main case where induced electric fields could be below the detection range, though this is considered unlikely, based on the movement of the animals and their proximity to the cable when they swam over it. Whilst theoretically there would be no movement of seawater in the tank at all, with a live animal moving around in the tank, this is an unrealistic assumption and clearly some minimal electric fields would be induced around the active cable before any induced by the animal itself.

It is most likely that the responses were prompted by the visual cue provided by the high contrast between the black cable and control hose against the white tank, as well as the tactile cue of the cable and control hose rising above the tank bottom. Visual and tactile cues are both used by elasmobranchs in conjunction with whatever other cues are available, including electrosensory cues (McComb & Kajiura, 2008; Jordan*, et al.*, 2009b; Gardiner*, et al.*, 2012).

It is important to reiterate that the rays crossed through the EMFs associated with the active cable (a non-response) the majority of the time, so whilst the EMFs may have had an effect, the predominant behaviour was that of non-response. The difficulty in teasing out whether the observed behavioural responses were prompted by other cues or simply random led to development of the experimental approach.

The design of the experimental tank and methodology were improved to remove the potentially confounding visual and tactile cues, and this improved design was used in both Chapters Four and Five, for the experiments investigating submarine AC power cables and the higher-current DC cables, respectively. The experiments with the 30 A DC cable also led to the design of a method to achieve EMFs that would be induced around power cables that would be used for OREDs, without requiring the dangerously high electrical currents that would normally pass through such cables.

Consequently, the behavioural effects of EMFs that would be induced around a 198 A submarine DC power cable were investigated, using New Zealand carpet sharks as a study species, as reported in Chapter Five. The overwhelmingly clear response of the sharks towards the active cables was to cross them, which happened 90.9% of the time, compared to investigating and avoiding the active cables 8.1% and 0.9% of the time, respectively.

Similarly to the AC experiments, the sharks actually showed more avoidance responses to the switched-off cables than to the active cables, again suggesting that most of the avoidance responses observed were most likely simply the shark changing swimming direction whilst it happened to be in the cable zone. It is clear from this and the overall very low incidence of avoidance responses that the EMFs around the active DC cables certainly did not cause discomfort to, or deter the sharks, and that they were able to cross through the cable zones unimpeded, and in fact did so the vast majority of the time.

Contrary to the AC experiments, however, where no instances of investigation were observed, investigation of the active DC cables occurred 8.1% of the time, showing that whilst crossing was the predominant behaviour, the sharks did respond to the EMFs and, thus, the EMFs did have a behavioural effect, albeit a small one. Interestingly, there was no statistical difference in investigation when sharks were foraging versus not.

Only two instances of investigation towards the switched-off cables were recorded, both during experiments with an olfactory stimulus added so the sharks would have been foraging and likely just investigated that area of the tank by chance. Whilst this suggests that some of the observed investigations may have also been false positives, it is unlikely that all of them were, and a statistically significant difference in frequency of investigation between switched-on cables and switched-off cables was found, further backing this up.

6.2.3 Habituation of elasmobranchs to submarine power cables

The behavioural response shown to the DC power cables by New Zealand carpet sharks prompted the question of whether this was a sustained effect or whether the sharks habituated to the presence of the EMFs over time. As described in Chapter Five, each experiment was split into 5-minute segments and the frequency of each behavioural response over the course of the experiments was compared. Whilst in olfactory experiments, the sharks were incited to forage by the addition of an olfactory stimulus at the start of an experiment and were thus more active in the first five minutes, they were active throughout the experiment and crossed the cable during all time segments (refer to Figure 5.4). They were active throughout the non-olfactory experiments, too, although more variably so, and also crossed the cable during all time segments (refer to Figure 5.3).

All but one instance of investigatory behaviour towards the cable (whether on or off) occurred in the first five minutes of an experiment. There was no statistical difference in the distribution of investigatory behaviour towards the switched-off cables, which is unsurprising given the low occurrence of investigation of switched-off cables in the first place. However, the sharks investigated the switched-on cable significantly more often in the first five minutes than in any other time segment of the experiment, regardless of whether or not an olfactory stimulus was added. Given that the sharks were active throughout the course of the experiments, this indicates that the sharks were either habituating to the EMFs or learning that they did not represent a food source.

Associative conditioned learning to various cues, including electromagnetic cues, has been demonstrated in a number of shark species, predominantly through the use of food rewards. Habituation to auditory stimuli in a number of species has also been demonstrated (Guttridge*, et al.*, 2009). Of particular interest is a study which looked at both learning and habituation to non-biological electric fields in lesser-spotted dogfish (*Scyliorhinus canicula* Linnaeus, 1758), and found clear evidence of both. Most individuals learned to associate electric fields with food rewards, whereas individuals who were not given a food reward showed clear habituation. After three weeks, no evidence of the previously learned or habituation behaviours was found (Kimber*, et al.*, 2013).

Memory retention in *S. canicula* lasted between 24 hours and three weeks, which ties in with the memory retention times shown by Port Jackson sharks (*Heterodontus portusjacksoni* Meyer, 1793) which ranged from 24 hours to potentially 40 days (Kimber*, et al.*, 2013; Guttridge & Brown, 2014). Whilst New Zealand carpet sharks showed habituation to the EMFs around the cables, and this lasted over the course of a 20-minute experiment, there was no observed effect on future experiments, run at least 2.5 hours later, though this could not be tested. This would suggest that either the memory retention time of *Cephaloscyllium isabellum* is much shorter, or that longer memory retention times were hard to perceive due to the limited number of observed behavioural responses. Based on personal observations and anecdotal evidence from local fishermen, it seems likely that *C. isabellum* has lower cognitive abilities compared to other similarly-sized sharks, so shorter memory retention rates would not be particularly surprising.

Given the extremely high non-response rate, high likelihood of the few observed instances of avoidance being random and only one instance of undirected swimming behaviour, habituation to the EMFs around the AC power cables was not tested as it was not deemed necessary.

6.3 Impacts of submarine power cables on benthic elasmobranchs

Submarine AC power cables are generally only used over distances up to 40 km, due to constantly changing polarity which means the cables can carry less power than an equivalently-rated DC cable. Generally AC cables are used for transporting electricity to near-shore islands or lighthouses. DC cables are commonly used for relaying electricity from OREDs to land or over longer distances than AC cables, for example across large bodies of water between countries. The number of submarine power cables, whether AC or DC will continue to rise as we continue to expand into the oceans, particularly with increasing numbers of ORED proposals (Gill*, et al.*, 2014).

The over-arching question that underpins this thesis is whether submarine power cables are likely to have an impact on benthic elasmobranchs. It is crucial to remember that effects do not necessarily translate into biologically-concerning impacts, and that there are a number of factors to consider when assessing this, including occurrence (single *vs*. multiple) and duration of effects (acute *vs*. chronic), and whether the effects are at an individual, population or species level (Boehlert & Gill, 2010; Gill*, et al.*, 2014).

6.3.1 Impacts of submarine AC power cables

The 50 Hz AC power cables that were tested produced a very limited behavioural effect in New Zealand carpet sharks, suggesting that submarine AC power cables are unlikely to have much of an impact. Whilst clear avoidance responses towards the active cable would have been greatly concerning and indicative of potential impacts, the random nature of the avoidance responses negates such concerns. However, the observation of a undirected swimming response, where the shark vigorously shook its head as it swam through the cable zone and then swam around in an undirected manner for a few seconds before resuming normal swimming patterns, was concerning. As such, this undirected swimming behaviour occurred only once out of a total of 526 interactions with the cable, suggesting that although a concerning behaviour, it is also quite a rare one. This rarity largely reduces the severity of potential impacts.

Based on the results described in Chapter Four, combined with the apparent low sensitivity of elasmobranchs to fields as high as 50 Hz, AC submarine power cables are not expected to have any particular negative impacts on benthic elasmobranchs. However, a previous study has indicated that some benthic elasmobranchs may be attracted to 100 A submarine AC power cables, which, although this appeared to vary on an individual basis, suggests that further investigation into a potential behavioural threshold is required (Gill*, et al.*, 2009).

There has been some recent investigation into the possibility of using high voltage low frequency AC (LFAC) power cables to improve power transmission efficiency compared to standard AC power cables. These cables would operate at 16.6 Hz or 20 Hz, which is much closer to the peak response frequencies of 2-4 Hz shown by elasmobranchs, and thus more likely to have an impact than the 50 Hz cables tested in Chapter Four (Montgomery & Bodznick, 1999; Manohara & Sonia, 2014). If the use of submarine LFAC power cables is pursued, investigation into the impacts of the associated EMFs is promptly required to address these concerns.

6.3.2 Impacts of submarine DC power cables

Based on the confounding presence of visual and tactile cues in the experimental set-up when testing the low-current DC cables, it is difficult to draw many confident conclusions on the potential impacts of such cables. However, the eagle rays did cross the active cable most of the time, suggesting that the EMFs around similar low-current DC cables are unlikely to have much of an impact. However, the use of such low-current DC cables is rare and so elasmobranchs are also unlikely to encounter one.

More crucially, when effects of the equivalent of a 198 A DC power cables were investigated, a behavioural effect was seen in New Zealand carpet sharks. Much like for the AC experiments, clear instances of avoidance of the active cables would have raised serious concerns, however, the few instances of avoidance behaviour of the DC cables were concluded to be largely random. The main effect observed was that of investigatory responses shown towards the active cable 8.1% of the time. Investigation of the cables is considered less concerning than complete avoidance of the cables, but if investigation occurred over a sustained amount of time or frequently, it could amount to significant energy wastage whilst foraging for phantom prey, which, in turn could impact an individual's fitness and chances of survival.

Moreover, the sharks appeared to habituate to the EMFs associated with the active cable or learn that they did not represent food within the first five minutes of an experiment, which suggests that the sharks are not likely to continue foraging around a cable zone unnecessarily for a sustained amount of time. This habituation did not appear to last between experiments, so currently appears short-term, but it is possible that the sharks' memory retention would be increase if the cable was on for longer, which would also be more representative of field conditions, and thus necessitates testing in the future.

The clear and significant investigatory response shown by the carpet sharks towards the DC power cables tested in Chapter Five suggests that the EMFs associated with such cables do have an effect, albeit a small one. That the effect is small, coupled with the relatively rapid habituation demonstrated by the sharks, suggests that impacts of DC power cables of 200 A and below are likely to be minimal. Even if the habituation is only short-term, the speed at which the sharks re-habituate suggests that this is unlikely to be an issue.

6.3.3 Impacts on movement and navigation of benthic elasmobranchs

One of the main concerns surrounding the increasing use of power cables in the marine environment was the potential for the EMFs associated these cables to overwhelm elasmobranchs' electrosensory systems and deter them, preventing them from crossing over the cables. This could evidently have major consequences in terms of movement of populations. However, no definitive occurrences of avoidance behaviours towards any of the cables specifications tested in this thesis (AC, low-current DC and higher-current DC) were observed, and the observation of avoidance behaviours towards the switched-off cables led to the conclusion that the observed avoidances were, in fact, largely random. This allows us to conclude that submarine power cables are not expected to impede the movement of sharks in any impactful way.

A rare, single occurrence of undirected swimming behaviour observed in one shark when encountering the EMFs in the AC cable zone suggests that the EMFs around AC cables may have a slight effect, but it is an insignificant one and not deemed likely to translate into an impact.

Elasmobranchs also use their electrosensory system for navigation, using the Earth's geomagnetic field (Meyer*, et al.*, 2005). It is not clear whether elasmobranchs directly detect the Earth's geomagnetic field or whether they use the weak electric fields induced by seawater movement through it (von Arx, 1962; Montgomery & Walker, 2001). Regardless, submarine power cables crossing through the geomagnetic field are likely to interfere with the EMFs, and, consequently, may have a behavioural impact. This is difficult to draw conclusions on based on the experiments conducted in this thesis and further preferably field-based experiments are required, however, there are a few points to note.

Experiments with nurse sharks (*Ginglymostoma cirratum* Bonnaterre, 1788) found that a background electric field appeared to increase the sensitivity of the animals' electrosensory systems (Johnson*, et al.*, 1984). Consequently, when encountering submarine power cables in the field, elasmobranchs' electrosensitivity may be enhanced by the background geomagnetic field, and responses may differ from those observed in a laboratory setting. Even though electrosensitivity in the ocean may (or may not) be enhanced, the Earth's geomagnetic field changes very slowly, so the cables are likely to appear as a very localised difference in signal against the relatively uniform background EMFs and are thus not expected to cause any great confusion in terms of navigation (Normandeau*, et al.*, 2011). Additionally, elasmobranchs swimming in the water column are not likely to be affected, due to the rapid attenuation of EMFs around power cables.

6.3.4 Impacts on foraging of benthic elasmobranchs

The EMFs associated with the higher-current DC cables did prompt a small investigatory behavioural effect, although as detailed above, any impacts are likely to be minimal at most. The presence of EMFs in conjunction with other cues, such as visual and tactile cues, may prompt more of an investigatory response, as seen with the eagle rays in conditions of seawater flow in Chapter Three.

No investigatory responses at all were prompted by the AC cables, which suggests that concerns around foraging impacts currently lie with the use of DC cables. However, there is evidence of at least some individual elasmobranchs showing attraction towards a submarine AC power cable in a field experiment and, when given a choice between an AC and a DC electric field of the same strength, lesser spotted dogfish showed a preference for the AC fields (Gill*, et al.*, 2009; Kimber*, et al.*, 2011). Evidently, other AC specifications or configurations may produce different results, as may other DC configurations, so further investigation is recommended.

6.3.5 New Zealand eagle rays and New Zealand carpet sharks as study species

The experiments throughout this thesis were conducted using either New Zealand eagle rays or New Zealand carpet sharks, and those on which most of the above conclusions are drawn were conducted with the sharks. These particular species were chosen for their ease of availability and, in the case of the carpet sharks, their low levels of stress in captive environments and rapid post-handling recovery.

It is important to note that electrosensory sensitivity varies across species, with rays generally accepted as having lower sensitivity thresholds and a better ability to pinpoint the source of electric fields due to the morphology of their electrosensory system, and also more reliant on it (Kajiura*, et al.*, 2010; Gardiner*, et al.*, 2012). Thus the behavioural responses shown by one species are evidently unlikely to be representative of the behavioural responses of all benthic elasmobranchs.

However, given the current paucity of research into the impacts of submarine power cables on elasmobranchs, these conclusions provide a useful starting point from which further studies should follow, using different cable specifications and study species, to broaden our understanding of how different species may respond to the EMFs associated with submarine power cables, and enable more widely-adaptable conclusions to be drawn, in terms of informing EIAs and, ultimately, legislation.

6.3.6 Directions for future research

Clearly the specifications of the cables tested in this thesis represent merely a small portion of the range of possible specification and configurations and conditions (such as seawater flow velocity and direction) that can exist in the field. Investigating more possibilities is obviously required, and it is imperative that the specifications studied in the future are strategically chosen in order to maximise the breadth of possibilities that conclusions can be confidently applied to. If LFAC power transmission is pursued, the lower frequencies at which these would be run should also be investigated. Studying different specifications will also direct any research into mitigation measures, such as burial of the cables, should they be required. Burial reduces the EMFs at the substrate surface by increasing the distance between the cable and the substrate surface, ideally so that the EMFs are below the elasmobranch detection threshold. The burial depth required for this would depend on the parameters of each particular situation (electrical current through the cable, seawater velocity and angle), the elasmobranch species are found in the area and would need to be evaluated on a case-by-case basis.

It is evident that not all benthic elasmobranch species have the same electrosensory sensitivity or reliance, and are thus unlikely to all show the same behavioural responses to the EMFs associated with submarine power cables. Consequently, it is imperative that further studies investigate the impacts of submarine power cables on other species. Rays, in particularly, are likely to be especially sensitive to EMFs. The long acclimation periods to the laboratory setting and to new tanks required by the New Zealand eagle rays precluded further experiments with them, but with different tank set-ups their stress levels could be reduced and perhaps further experiments conducted. Investigating the impacts on different life stages of the same species is also important, as cables running through nursery areas could have different impacts than cables located elsewhere. Analysing the proportion of time that experimental animals spend in areas of the tank where the EMFs are within the known detection range would also be an interesting way to investigate the attraction effect of submarine power cables.

In addition to expanding the range of species investigated, field experiments must also be conducted in order to better understand how different cues and environmental factors interact with each other. Whilst impacts appear limited based on tank studies where the only cues available to the animals are the EMFs (and olfactory cues in some cases), these cues may produce an impact when interacting with other unforeseen factors. A mesocosm study has been conducted with submarine power cables, which, although not able to draw conclusions on impacts, did show some behavioural movements and responses towards the active AC cables (Gill*, et al.*, 2009, 2014).

Laboratory experiments, such as those conducted in this thesis, are useful and necessary in terms of providing a foundation in terms of determining behavioural thresholds or response differences between species or between different life history stages or sexes within a species. This understanding can then be built on through larger-scale field studies, perhaps similar to the aforementioned mesocosm experiments, where more potentially confounding factors will be involved. Laboratory and field studies are equally necessary and complement each other in addressing whether the EMFs associated with submarine power cables have any impacts on benthic elasmobranchs.

6.4 Summary of conclusions

The experiments and conclusions discussed within this thesis form a necessary foundation for investigating the potential impacts of submarine power cables on benthic elasmobranchs, and begin to address the paucity of studies conducted so far. The conclusion from the limited behavioural responses observed in this study is that the EMFs associated with submarine AC power cables do not pose any concern and are not expected to have any negative impacts on benthic elasmobranchs. The EMFs associated with submarine DC power cables may prompt investigatory responses, but animals are expected to habituate to these fields, and they are not expected to translate into concerning impacts. However, there are several caveats that go along with these conclusions, namely that these conclusions are largely based on the behaviours observed in New Zealand carpet sharks and are unlikely to be completely representative of all benthic elasmobranchs, that there are many different submarine power cable specifications and possible configurations and impacts are likely to be different across the range of possibilities, and that all experiments were conducted in tanks, which, whilst an important study, may not entirely reflect responses that would occur in the field, when additional cues and environmental factors are present. These current limitations can and should be addressed through future experimentation, in order to increase the confidence in the above conclusions, with the view of presenting the most accurate guidance possible for EIAs or to inform legislation.

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