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Behavioural response of benthic elasmobranchs to a neodymium magnet under controlled laboratory conditions

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A R T I C L E I N F O

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A B S T R A C T

Global elasmobranch population decline can be largely attributed to anthropogenic impacts such as commercial fishing. As such, reducing bycatch of these animals is a key management objective in many fisheries. Magnetic deterrents such as permanent and rare-earth magnets can deter both pelagic and benthic elasmobranch species. However, the literature is inconsistent and shows varied levels of effectiveness depending on the species and the deterrent. To broaden our understanding of species-specific differences in deterrent effectiveness, this study assessed the efficacy of a rare-earth magnet to deter four benthic elasmobranchs under laboratory conditions: Port Jackson shark (*Heterodontus portusjacksoni*; $n = 10$), epaulette shark (*Hemiscyllium ocellatum*; $n = 8$), eastern fiddler ray (*Trygonorrhina fasciata*; $n = 10$), and the blue spotted mask ray (*Neotrygon kuhlii*; $n = 7$). After evaluating the behavioural response of the four study species in the presence of a N52 neodymium magnet and a control in 207 trials, the neodymium magnet did not effectively prevent individuals from entering an experimental compartment. The magnet only had a minor deterrent effect, slightly reducing the proportion of successful attempts at entry through the door and over the neodymium magnet (control: 0.94 ± 0.23; neodymium magnet: 0.74 ± 0.3; mean ± standard deviation). We hypothesised this was a result of species-specific biological and behavioural factors that reduce the effectiveness of magnets as deterrents for these species. Our results suggest fisheries management moves away from trialling magnets as elasmobranch deterrents due to their inconsistent effectiveness, and rather investigate other devices such as those using electrical fields that show greater potential.

1. Introduction

Globally, elasmobranch populations have been on a decline due to commercial fisheries (Dulvy et al., 2008; Dulvy et al., 2014; Stevens et al., 2000). This has led to calls for elasmobranch-specific mitigation devices to reduce bycatch and catch effects while maintaining the catch of target species. Traditional mitigation devices consist of gear modifications such as circle hooks that latch onto the jaw instead of the oesophagus or gut like traditional J hooks, reducing catch effects (Cooke and Suski, 2004). While these modifications have sometimes been successful for elasmobranch mitigation in commercial hook and line/longline fisheries, there has been a rise in studies investigating the concept of overstimulating the electrosensory system of elasmobranchs, the ampullae of Lorenzini, as an elasmobranch-specific mitigation method for passive commercial fishing techniques such as traps and gillnets.

The ampullae of Lorenzini are an elasmobranch-specific electrosensory system that allows elasmobranchs to detect weak magnetic fields given off by potential prey, predators, conspecifics, and the Earth, and overstimulating these organs has a high deterrent effect (Kalmijn, 1966; Kalmijn, 1972; Kalmijn, 1982). Previous studies investigating the use of permanent rare-earth magnets that achieve this effect to reduce elasmobranch bycatch have been variable in their effectiveness, with differences attributed to study conditions, species, and types of magnet used (Table 1). Previous research has shown a higher rate of deterrent effects in benthic (Jordan et al., 2011, Smith and O'connell, 2014, Westlake et al., 2018) rather than in pelagic species (O'connell et al., 2011a; Siegenthaler et al., 2016), as benthic species rely more heavily on electroreception for foraging over other senses due to the typically cryptic nature of their prey (Kempster et al., 2012). Despite this higher reliance and risk of being caught in fishing gear due to their shallow and narrow depth range (Dulvy et al., 2014), there is less research on how

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benthic elasmobranchs respond to magnetic deterrents. The variability between conditions and species calls for further testing of neodymium magnets to determine the reliability of this magnet type as an elasmobranch deterrent more broadly.

Around Australia's coastlines, benthic elasmobranchs inhabit close to or on the substratum of estuaries, coasts, and coral reefs, and are prone to interactions with passive fishing methods used in this area (Last and Stevens, 1994). Two benthic species that are endemic to Australian temperate environments and are commonly caught as bycatch in NSW longline and trap fisheries are the Port Jackson shark (*Heterodontus portusjacksoni*) and the eastern fiddler ray (*Trygonorrhina fasciata*) (Walker and Gason, 2007). Inhabiting Australian temperate and tropical waters, the blue spotted mask ray (*Neotrygon kuhlii*) is common bycatch in Australian trawl fisheries (Stobutzki et al., 2002). The epaulette shark (*Hemiscyllium ocellatum*) is a small tropical species found on shallow coral reef flats (Last and Stevens, 2009), is similar taxonomically and morphologically to carpet sharks frequently caught in these fisheries (e.g., Orectolobiformes, specifically *Brachaelurus waddi*), and was thus expected to be a suitable analogue to those species. These four species occupy a range of different ecosystems from estuaries to coasts to coral reefs (Last and Stevens, 1994). Given the high occurrence of these or similar species in fishing operations, there is a need to test mitigation devices to deter individuals from fishing gear such as benthic traps or nets across a range of different ecosystems.

The aim of this study was to determine if a rare-earth magnet would successfully deter elasmobranch species typically caught in commercial fisheries to provide empirical evidence for incorporation into a bycatch mitigation device. Under controlled laboratory conditions, *H. portusjacksoni*, *T. fasciata*, *N. kuhlii*, and *H. ocellatum* were observed in the presence and absence of a neodymium magnet. It was hypothesised that the four small elasmobranch species would display a behavioural deterrence response in the presence of the neodymium magnet and its magnetic field, with individuals not being able to pass through a door and reaching a bait attractant.

2. Materials and methods

2.1. Experimental conditions

Experiments were conducted at Irukandji Shark and Ray Encounters, Port Stephens, NSW. The test tank (2.8 m diameter by 0.9 m height, holding approximately 4kL of water) consisted of two sections separated by a barrier (baited and non-baited halves; Fig. 1), constructed using PVC pipe and small white mesh netting secured to the bottom similar to the design in O'connell et al. (2011b). This barrier had a "door" (1 m length and 0.4 m height), which would allow individuals free movement between sections during testing. However, prior to testing, a corflute sheet held down with lead weights blocked the door to ensure individuals did not pass through before trial commencement. Bait, secured with a peg and lead weight, was placed close to the door to entice the individuals through the door. The bait used was the regular diet of individuals, consisting of 4.2% of their body weight a week (personal communications: Irukandji Shark and Ray Encounters (2020)), consisting of pilchards (*Sardinops sagax*), school prawns (*Metapenaeus macleayi*), and Californian Logio Squid (*Loligo opalescens*). Uneaten bait was removed from the tank after each trial and replaced with fresh bait to reduce bias and maintain healthy water parameters. To record elasmobranch response and behaviour, a GoPro Hero 7 Black camera recording at 1080p and 30fps was hung above the tank looking downwards in a way it could view the entire experimental setup.

The experimental tank was a closed system, with water sourced from Little Beach Reserve, Port Stephens and passed through ozone and ultrafiltration before use. The tank was fitted with a sand- and bio-filter, and protein skimmer, and the tank water was replaced weekly to reduce the possibility of build-up of excess nutrients and stress hormones such as cortisol (Reid and Perry, 1991; Schreck, 1981). Water quality parameters such as ammonia, nitrate, nitrite, and phosphate were recorded each morning as part of the normal operating procedures of the aquarium prior to experimentation, and experimental trials did not occur if those levels were not within acceptable ranges. The mean temperature for the experimental tank was 19.6 °C ± 0.2 °C, with salinity and pH kept at a constant 32 ppt and 8.1, respectively. When individuals were not being tested, they remained in their separate

Table 1
Summary of previous studies investigating the effects of neodymium magnets on elasmobranchs. B = benthic species (species inhabiting the bottom of the ocean; Last and Stevens (2009); P = pelagic species (species inhabiting the water column; Last and Stevens (2009).

Magnet Type	Study Species	B/P	Condition	Success	Study
Neodymium-iron-boron	*Squalus acanthius*	B	Laboratory	No	Stoner and Kaimmer (2008)
Neodymium	*Squalus acanthias* *Mustelus canis*	B	Laboratory	Partial[a]	Jordan et al. (2011)
Neodymium-iron-boron EPM (neodymium and neodymium-praseodymium alloy)	*Carcharhinus galapagensis*	P	Longline	Partial[b]	Robbins et al. (2011)
Barium-ferrite Neodymium-iron-boron	*Carcharhinus limbatus* *Carcharhinus plumbeus* *Dasyatis americana* *Mustelus canis* *Raja eglanteria*	B/P	Longline Recreational fishing	Partial[c]	O'connell et al. (2011a)
Neodymium-iron-boron	*Scyliorhinus canicula* *Raja clavata*	B	Laboratory	Yes	Smith and O'connell (2014)
N35 Nickel N35 Neodymium-iron-boron	*Prionace glauca*	P	Longline	No	Porsmoguer et al. (2015)
Neodymium-iron-boron	*Carcharhinus plumbeus*	P	Laboratory	Yes	Siegenthaler et al. (2016)
Neodymium-iron-boron	*Cephaloscyllium laticeps*	B	Field	Partial[d]	Westlake et al. (2018)
Neodymium	*Carcharhinus taurus*	P	Laboratory	No	Polpetta et al. (2021)
DC 12 V 180 N electromagnet N52 Neodymium	*Carcharhinus leucas*	P	Field	Partial[e]	O'connell et al. (2022a)
N52 Neodymium C8 Barium-ferrite	*Carcharhinus leucas*	P	Field	Partial[e]	O'connell et al. (2022b)

[a] In the presence of conspecifics, individuals displayed reduced aversion to the magnet.
[b] Found success in two configuration types but no success in the others.
[c] The success rate of the magnets varied between species.
[d] Variable success across individuals and over time
[e] Did not deter all interacting individuals

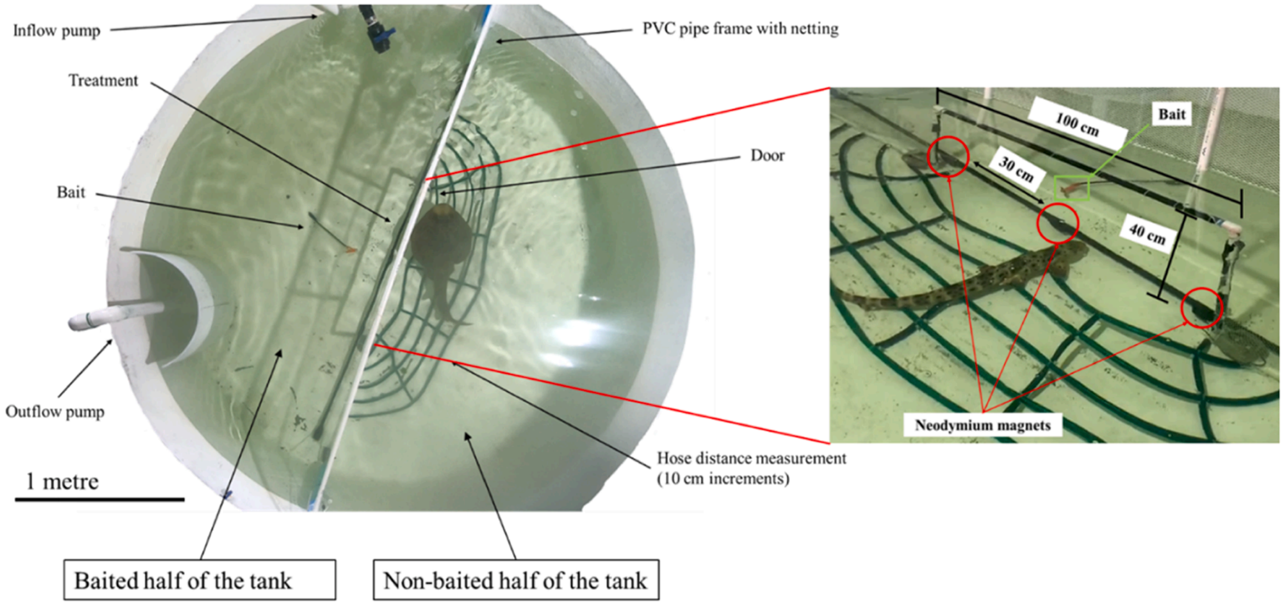

Fig. 1. Camera view of the experimental tank set up for the present study.

housing tanks that were part of an interactive aquarium and were available to the public.

2.2. Experimental design

The behaviour of the four study species was observed in the presence of both a control (a piece of dowel wrapped in black tape) and a magnetic treatment: three N52 rare-earth neodymium magnets (40 mm × 15 mm x 8 mm) placed 30 cm apart on a piece of dowel wrapped in black tape, each with a field strength of 4153 Gauss. During each trial treatment type alternated from the previous one, and individuals from the pool of each species were randomly chosen to participate in a given trial due to difficulties capturing them in their main holding tanks. Towards the end of the experiment (e.g., when most individuals had completed 2 of 3 trials of each treatment) individuals were selected specifically to complete the remaining replicates. The chosen treatment was placed across the threshold of the door (within 2 cm of the threshold) so that the individual must pass through the door and over the treatment to reach the bait placed on the other side. The magnet was deemed ineffective if the individual could consistently pass through the door (and thus over the magnet) without hesitation. The magnet was deemed effective if the individual tried to go through the door but was not successful due to the presence of the magnetic treatment at the threshold. To analyse this, we looked at the proportion of successful attempts at crossing over this threshold relative to the total number of attempts made by an individual per trial. The time it took the individual to obtain the bait once successfully passing over the door the first time was recorded as an indicator of habituation to the magnet or the novelty of the experiment. The individuals that were chosen varied in size and sex (Table 2) within each species. Each individual was exposed to each treatment (control and magnet) on three separate occasions, with each individual being trialled a total of six times over five months (May 2020 to September 2020). The individuals and treatments were chosen at random for each trial to avoid order effects, as well as to limit habituation effects. No individual was trialled more than once within a five day period to reduce stress. The interval between treatment exposures for each individual ranged from one week to one month and similar time intervals between trials.

Table 2
Summary of study species (TL = Total Length. DW = Disc Width). Different sample sizes were attributable to availability.

Species	n	Size range (cm)	Number of males	Number of females
Heterodontus portusjacksoni	10	58 – 87 (TL)	0	10
Hemiscyllium ocellatum	8	65 – 93 (TL)	2	6
Trygonorrhina fasciata	10	71 – 91 (TL)	2	8
Neotrygon kuhlii	7	34 – 57 (DW)	3	4

2.3. Experimental procedure

Individuals were collected from their housing tank one at a time and temperature acclimated in the experimental tank. The duration of this acclimation was developed for each species as the optimal acclimation time period (personal communications: Irukandji Shark and Ray Encounters (2020)), with *H. portusjacksoni* and *T. fasciata* acclimating for 3 mins per degree, *N. kuhlii* acclimating for 4:30 mins per degree, and *H. ocellatum* acclimating for 5:46 mins per degree. *H. ocellatum* individuals were trialled first after weekly water changes to reduce temperature acclimation time since fresh tank water had a similar temperature to the tropical holding tank. After the acclimation period, individuals were placed into the non-baited half of the tank (Fig. 1) to undergo a 30-minute stress acclimation following the methods of Jordan et al. (2011). During this time the behaviour of individuals were monitored for relaxed behaviours such as calm swimming patterns and slow ventilation rates (Barker et al., 2011; Raoult et al., 2019). After this acclimation period and when the individuals displayed relaxed behaviours, the trial commenced. All individuals displayed relaxed behaviours within the 30-minute acclimation period for all trials. It was possible that stressors occurred prior to trials in main holding tanks (public handling and viewing), however, individuals showed no signs of stress within their interactive aquarium where they were hand fed and touched by the public.

Prior to the removal of the barrier "door", a piece of bait was placed into the baited half of the tank, 10 cm from the door and treatment (Fig. 1). The treatment (control or magnet) was then placed along the door threshold immediately prior to the commencement of the trial, to reduce pre-exposure. The cameras were set to record, and the doors were removed, signifying the commencement of the trial. To avoid habituation, each trial lasted 20 min, as Rigg et al. (2009) observed habitation occurring after 30 min in laboratory conditions. Once the 20 min were finished, the camera, uneaten bait and treatment were retrieved from the tank. The individual was then collected and acclimated back into their holding tank. During acclimation and the trial, interactions such as looking into the tank were avoided by the observers.

2.4. Video analysis

Video footage obtained from the GoPro was reviewed using VLC media player and analysed for a range of behavioural parameters (Table 3).

2.5. Data analysis

To observe any effect of the magnet or control on the time for individuals of a species to obtain the bait, a linear model was used with time to obtain bait as the dependent variable with species and treatment as fixed factors with an interaction between treatment and species. Time to bait values were transformed with a natural logarithm. To determine if there were habituation effects over time, a linear model similar to the above was used, but with replicate number as an added continuous determinant. A LOESS smoothing curve was fitted to the figure with a 95% confidence interval, a 75% span and evaluated at 80 points.

Since some individuals remained stationary for the duration of the trial, a behaviour we termed "rested", it was necessary to separate those that attempted to move into the other compartment from those that did not, so a separate dataset was created that included only the trials where individuals attempted to move into the second compartment. A Generalised Linear Model (GLM) was used to determine the effect of treatment on the proportion of successful attempts to pass over the door for each individual of a species. The proportion of successful attempts was the dependent variable with species and treatment as fixed factors with an interaction between species and treatment. The model was fitted with a quasibinomial distribution with a logit link, as per Zuur et al. (2009), as quasibinomial families are optimal for proportional data. All statistical analysis was carried out in R statistical software version 4.0.2 (RSTUDIO Team, 2021).

3. Results

A total of 207 trials were conducted on the four-elasmobranch species ($n = 35$ individuals in total; Table 2), with 103 trials with the neodymium treatment and 104 trials with the control treatment. There were 3 trials that were not completed due to two *H. ocellatum* individuals dying in the main holding tank (from factors separate to this experiment) and a *T. fasciata* individual mistakenly not included. In 79 trials, individuals did not pass through the door and in 158 trials, individuals did not obtain the bait (Table 4). *H. ocellatum* and *T. fasciata* were not included in the analysis of time to obtain bait due to insufficient data (Table 4).

Table 3
Behavioural characteristics of elasmobranchs recorded from video footage.

Recorded Parameter	Unit	Definition
Number of attempts	Count	This was categorised as any movements by an individual towards the "door" from any direction that was not in their normal observed swimming patterns throughout the trial
Successful attempt	Count	This was categorised as the individual's entire body passing through the door throughout the trial
Proportion of successful attempts	Proportion	The number of successful passes through the door (and over the treatment) divided by the overall number of attempts at passing through the door (and over the treatment) for each individual of a species
Time to obtain bait	Seconds	This was categorised by how long the individual took to first obtain the bait once successfully passing over the door the first time

3.1. Passes through the door

There was a significant difference in the proportion of successful attempts to pass through the door between the two treatments ($p < 0.01$; Fig. 2), however, there were no significant differences between species, nor were there interactions between species and treatments ($p > 0.05$; Fig. 2). Variation between the number of successful passes through the door (attempts) over the total number of attempts at passing through the door for each species indicated no consistent effect of the magnet. However, it appeared that *H. ocellatum* and *N. kuhlii* were less likely to pass over the magnet treatment than the other two species, indicated by the median proportion of successful attempts to pass through the door decreasing from 1 to 0.39 for *H. ocellatum* and 1 to 0.71 for *N. kuhlii* in the presence of the neodymium magnet (Fig. 2).

3.2. Time to obtain bait

The magnet was not effective at preventing study species from entering the baited half of the tank (Table 4). There was no significant difference observed in the time it took both species to obtain the bait (*H. portusjacksoni*: control 78 s ± 112 s, neodymium 158 s ± 180 s; *N. kuhlii*: control 163 s ± 296 s, neodymium 43 s ± 76 s; mean ± standard deviation; Table 4). When exposed to the magnet or the control (df = 1, F = 0.45, p = 0.50) and no interaction between treatment and species (df = 3, F = 0.96, p = 0.41). There was no measurable habituation effect, as time to take the bait did not change significantly over time for individuals regardless of treatment (df = 1, F = 0.44, p = 0.51; Fig. 3).

4. Discussion

The findings from this study indicate that the neodymium magnets did not form a barrier to entry into the experimental compartment, with all species crossing over the magnets into the experimental compartment. However, neodymium magnets do seem to have a weak deterrent effect, as the proportion of successful attempts to enter the baited half of the tank was lower when neodymium magnets were present. These results were consistent with other laboratory and field studies which were unsuccessful in deterring elasmobranchs in the presence of magnets, but do highlight that elasmobranchs are likely able to detect their presence and they may have weak deterrent effects (Porsmoguer et al., 2015; Robbins et al., 2011; Stoner and Kaimmer, 2008).

The variable deterrent effects that were detected in the presence of the neodymium magnet could be a product of the sensory capabilities of the species: the distribution and abundance of ampullae of Lorenzini is variable among species of elasmobranchs due to the influence of morphology, phylogeny, habitat and feeding ecology (Kempster et al., 2012; Newton et al., 2019). These differences in response to the magnets align with the densities of ampullae of Lorenzini, where species with higher densities should have higher sensitivity to magnetic fields, and the two species that showed more of a response to the presence of magnets had the highest known concentrations of ampullary pores (*N. kuhlii* and *H. ocellatum*) between the four study species (Newton et al., 2019; Winther-Janson et al., 2012). Difficulty identifying species-specific effects could be a result of too little replication. Kempster et al. (2016) documented similar results between *H. portusjacksoni* and the western shovel nose ray (*Aptychotrema vincentiana*), with *A. vincentiana* displaying a greater ability to accurately locate an electrical signal in comparison to *H. portusjacksoni*, despite having similar habitat and feeding ecologies. This difference was attributable to the differences in ampullary pore abundance, distribution, resolution, and

Table 4
Summary of results for each species per treatment.

Species	Treatment	Number of trials	Number of attempts	Number of successful attempts	Number of trials where bait was obtained	Mean time to obtain bait ± standard deviation (s)
Heterodontus portusjacksoni	Neodymium	30	99	83	11	158 ± 180
	Control	30	81	81	8	78 ± 112
Hemiscyllium ocellatum	Neodymium	23	124	59	1	941 ± NA
	Control	23	55	31	0	NA
Trygonorrhina fasciata	Neodymium	29	96	88	2	663 ± 716
	Control	30	54	54	1	360 ± NA
Neotrygon kuhlii	Neodymium	21	140	107	11	43 ± 76
	Control	21	108	105	8	162 ± 269

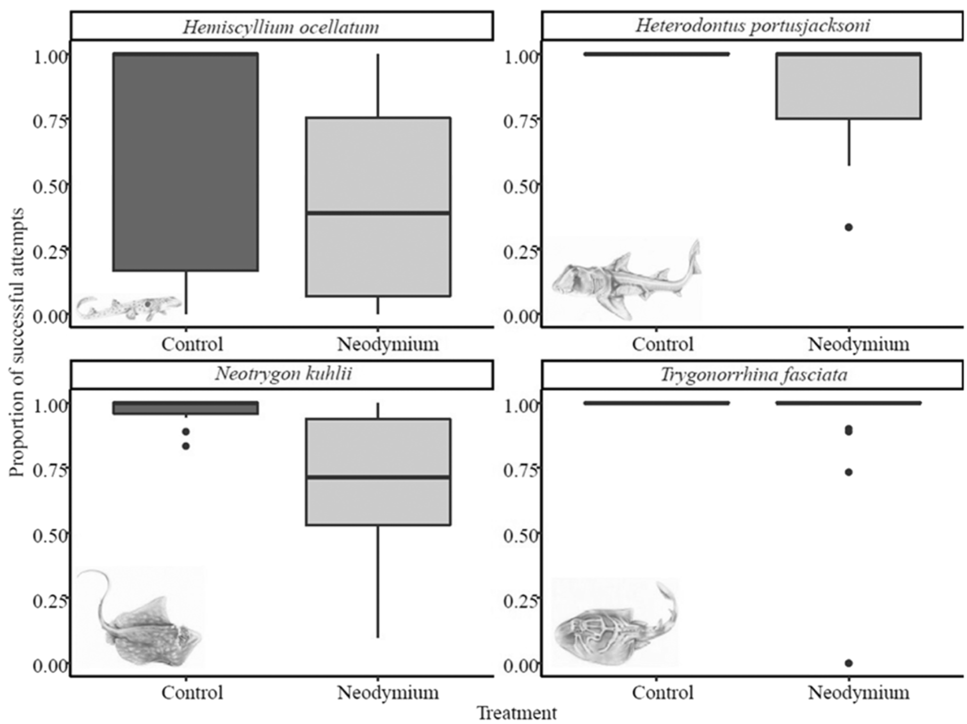

Fig. 2. Boxplot of the proportion of successful attempts to pass through the door (and over the treatment) per individual for each treatment (n = 2) and each species (n = 4), excluding tests that recorded individuals resting for the duration of the trial.

approach behaviours between the two species (Kempster et al., 2016). While our results suggest that higher concentrations of ampullary pores leads to greater sensitivity towards magnets, the magnetic deterrent effect was still weak at best. It is possible that studies incorporating magnetic deterrents in a fishery setting (e.g. Richards et al., 2018) are still able to use magnets to reduce bycatch in some passive fisheries (e.g. fish traps). However, despite these results, magnetic deterrents are unlikely to be sufficient to deter elasmobranchs from active fishing methods like benthic trawls that represent most of the threats to these species, given the short detection range of ampullae of Lorenzini (< 0.5 m) and the active nature and speed of trawls. Consequently, development of fisheries-based deterrents should instead focus on visual or electric deterrents that have shown higher levels of effectiveness in elasmobranchs (Raoult et al., 2023).

The feeding ecology and position in the water column of a species is a reflection of their diet and habitat use (Rigg et al., 2009). Benthic species, such as those in the present study, typically rely more heavily on electroreception for foraging than pelagic species due to their prey primarily being found on or within the substrate (Kempster et al., 2012). In contrast, the diet of pelagic species consists of more mobile and faster moving prey that require more visual foraging (Kempster et al., 2012). The typical prey of *H. ocellatum* consists of polychaetes, crustaceans, small fish, and amphipods; a diet that relies on electroreception to forage on and within the substrate over other senses such as vision (Heupel and Bennett, 1998; Last and Stevens, 1994). However, the diet of *H. portusjacksoni* consists of both demersal benthic and benthopelagic prey such as invertebrates and fish, resulting in a reliance on both vison and electroreception (Last and Stevens, 2009; Powter et al., 2010). All the species examined here have different diets and feeding ecologies, and this should lead to different responses to magnetic fields, however, no significant difference in response was observed. Despite the assumption that benthic species would be more sensitive to magnets compared to pelagic species, none of the species tested here showed a strong aversion to the magnets, indicating that in even more theoretically magnet-sensitive species, they are not effective deterrents. It is possible that the relatively low number of trials run per species made this harder to detect empirically, however, if magnets did have a strong deterrent effect we should still be able to detect this. These results suggest that rare-earth magnets are not consistently effective as deterrents in the species tested, despite some species higher dependence on electroreception for foraging.

The behavioural response of the individuals within each study species was variable despite the individuals within a species containing the same number of ampullary pores. This concept is consistent with previous studies with intra-species variations being observed in response to electrical and metal alloys (Hutchinson et al., 2012; Kajiura and

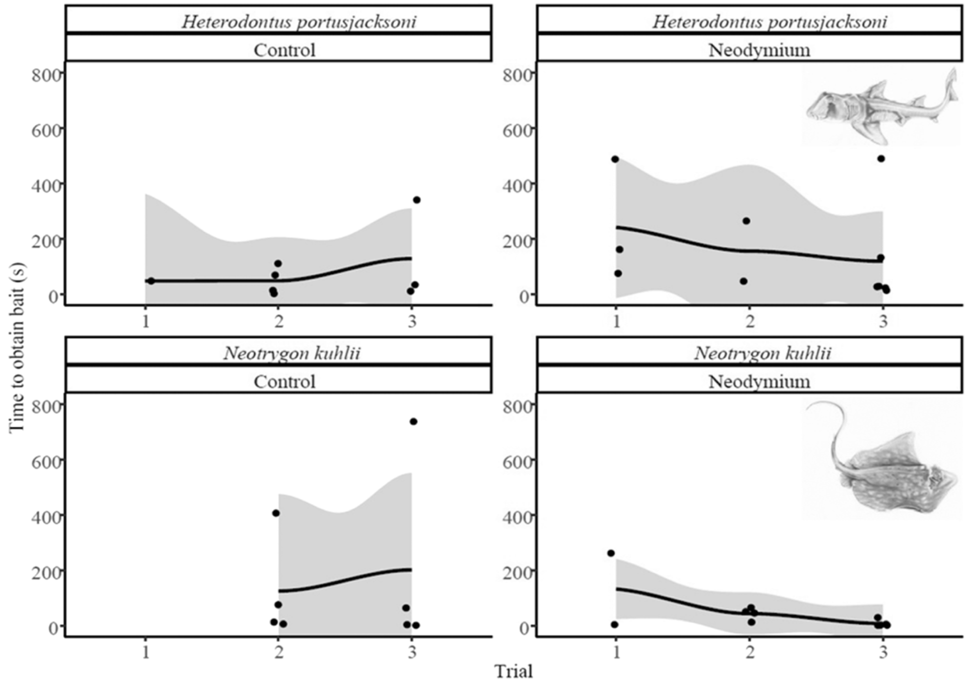

Fig. 3. Plot of the time each individual took to obtain bait over each trial (n = 3) for those individuals that did take the bait. H. ocellatum and T. fasciata were removed from this data set due to insufficient replication. A LOESS smoothing curve was used with a 95% confidence interval.

Holland, 2002). The differences between individuals could be attributable to differences such as motivation and personality (Raoult et al., 2012; Raoult et al., 2017; Westlake et al., 2018). The personality of individuals in a species, such as the boldness spectrum, could also have an impact on the response of individuals towards the neodymium magnet. Bolder individuals may be more likely to pass over the magnetic field and obtain the bait in comparison to docile individuals (Byrnes and Brown, 2016; Westlake et al., 2018). This concept has been extensively seen in captive reared fish such as mulloway (*Argyosomus japonicus*; Raoult et al., 2012, Raoult et al., 2017), bull trout (*Salvelinus confluentus*; Brignon et al., 2018), sole (*Solea solea*; MAS-Muñoz et al., 2011), and rainbow trout (*Oncorhynchus mykiss*; Sneddon et al., 2003). Elasmobranchs have also shown personality traits, including *H. portusjacksoni* assessed in Byrnes and Brown (2016) who indicated that this species can display bold personalities. In a novel open field study, bolder lemon sharks (*Negaprion brevirostris*) individuals were faster at exploring the field and displayed risky behaviours such as swimming further from shore (Dhellemmes et al., 2021). Boldness could have been a factor in our trials, with some individuals from each species not passing over the door for neither control nor neodymium magnet trials. Resting or making no attempts across the experimental treatment could have been indicative of shy personalities, while bold individuals may have been more likely to foray into the experimental treatment. Future studies should attempt to quantify the effects of personality, and the boldness spectrum in particular, on deterrence effectiveness.

In laboratory studies, food deprivation influences the effectiveness of a magnetic deterrent, and overfeeding could have been a factor in animals not attempting to cross through the door into the baited half of the tank (Stoner and Kaimmer, 2008; Tallack and Mandelman, 2009). Tallack and Mandelman (2009) observed that spiny dogfish (*Squalus acanthias*) were not deterred by the cerium and lanthanum mischmetal when deprived of food for 2 or 4 days prior to experimentation, however, when fed to satiation prior to experimentation, *S. acanthias* displayed avoidance towards the mischmetal, indicating food deprivation plays an important factor in deterrence. In the present study, food deprivation and satiation were not controlled, as experimentation was conducted at an interactive aquarium. This meant satiation levels of individuals were unknown, and likely high given the tendency to overfeed in these sorts of environments and could possibly explain the variability in the time to obtain bait between species and individuals.

In the housing tanks, the individuals were taught to respond to food, resulting in individuals being food motivated and positively responding to food in their holding tank, however, this was not observed in the experimental tank. A possible explanation for this could be due to stress, which would also reduce the likelihood of animals trying to move into the baited half of the tank. Stress on the individuals was reduced where possible; for example, the 30 min prior to experimentation to allow individuals to relax. The breathing rates of individuals were also observed and trials only commenced if the individual showed relaxed ventilation and swimming rates (Barker et al., 2011; Raoult et al., 2019). This could be another explanation for why individuals did not feed on bait; if an animal is stressed a reduction in feeding rates and feeding behaviours is typically observed (López-Olmeda et al., 2012). If stress were a factor, we would suspect a reduction of stress during successive trials, which the results did not display. Individuals were re-trialled in a time interval of a week to a month, a short time period where the movement of the individual is not perceived as a new stressor and thus we do not think our results were impacted by these effects. Another potential factor could be that the individuals were already desensitised to electrical and magnetic fields due to living around artificial sources in the aquarium.

5. Conclusion

This study represents a comprehensive investigation of the behavioural response in the presence of a magnetic field of four benthic elasmobranch species across a total of over 200 experimental trials under controlled laboratory conditions. Previously, most studies have only examined one or two species in the presence of neodymium magnets (Siegenthaler et al., 2016; Stoner and Kaimmer, 2008; Westlake et al., 2018). The number of trials used in this study was also high with few previous studies using such a high replication, 512 across two species (Jordan et al., 2011), 84 (Stoner and Kaimmer, 2008), 84 (O'connell et al., 2011a), and 58 (Smith and O'connell, 2014). In addition, no previous studies had tested the behavioural response of three of these four benthic elasmobranchs to a magnetic field (Kempster et al., 2016).

Permanent magnets were unsuccessful in strongly deterring benthic elasmobranchs from passing over the barrier door and obtaining the bait. This was possibly due to differences in ampullae of Lorenzini morphology, feeding ecologies, habitat, position in the water column, and individual personalities. The results from this study question the efficacy of magnets to deter elasmobranchs, and whether research should redirect to using electro-deterrents with higher success rates. Magnets had been thought as one of the best methods to reduce elasmobranch bycatch in commercial or recreational fisheries, however, as seen in this study and similar studies, the response is highly variable and often not significant. In future studies, new technological avenues should be explored for an elasmobranch-specific deterrent incorporating of wider range of elasmobranchs with different feeding ecologies.

Animal ethics

All research was conducted under the University of Newcastle Animal Ethics Committee approved protocol A-2013–354.

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CRediT authorship contribution statement

Molly Grew: Conceptualisation, Methodology, Formal analysis, Investigation, Writing – original draft. **Troy F. Gaston**: Funding acquisition, Conceptualisation, Methodology, Validation, Investigation, Formal analysis, Resources, Writing – review & editing, Supervision. **Vincent Raoult**: Conceptualisation, Methodology, Validation, Investigation, Formal analysis, Resources, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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