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Aversive responses of captive sandbar sharks (*Carcharhinus plumbeus*) to strong magnetic fields

Short title: *Carcharhinus plumbeus* responses to magnetic fields

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This experimental study focused on the possible deterrent effect of permanent magnets on adult sandbar sharks, *Carcharhinus plumbeus*. Results showed that the presence of a magnetic field significantly reduced the number of approaches of conditioned *C. plumbeus* towards a target; indicating that adult *C. plumbeus* can be deterred by strong magnetic fields. These data, therefore, confirm that the use of magnetic devices to reduce shark bycatch is a promising avenue.

Key words: Behaviour; Bycatch; Elasmobranch; Fisheries; Magnetoreception; Permanent Magnet

INTRODUCTION

Due to their low fecundity and late maturity, most shark species are highly susceptible to overfishing. In a study about large pelagic sharks in the Northwest Atlantic Ocean Baum *et al.* (2003; 2005) estimated a greater than 50% decline of populations in 8 to 15 years. On an annual basis, global mortality is estimated to range between 63 and 273 million sharks per year, which represents an average exploitation rate between 6.4% and 7.9% of the global population (Worm *et al.*, 2013). Sharks are vulnerable to even light fishing pressure, and the decline of these large predators results in community shifts that influence other vulnerable species such as marine mammals and sea turtles (Ferretti *et al.*, 2010). Apart from direct capture of sharks, shark bycatch also contributes to substantial shark mortality (Baum *et al.*, 2003; Verlecar *et al.*, 2007) in commercial longline fisheries (Stevens, 2000; Gilman *et al.*, 2008; Cortés *et al.*, 2010; Zhou *et al.*, 2011) and in beach nets (Cliff *et al.*, 1988; Cliff & Dudley, 1992; O'Connell *et al.*, 2014*a*, 2014*c*). Shark bycatch also results in personal injuries, lower catches, and loss of gear (Gilman *et al.*, 2008).

To reduce human injuries and shark bycatch, several shark repellents have been developed. Chemical shark repellents developed for the protection of humans (Gilbert, 1977) are only useful as a directional repellent and need to be delivered directly in the presence of sharks (Smith, 1991; Sisneros & Nelson, 2001). Gear modifications, such as the use of circle hooks instead of the often used j-shaped hooks appear promising (Kaplan *et al.*, 2007) but are not always successful (Read, 2007), and may even be harmful to other protected animals (Gilman *et al.*, 2008). Current shark repellent research focuses on permanent magnets and electropositive metal alloys (O'Connell *et al.*, 2014*c*). These operate by repelling sharks, making use of their ability to detect weak electric fields (as small as 5nVcm-1, *e.g.* Kalmijn, 1971; Haine *et al.*, 2001; Kajiura, 2003). Sharks can detect electric fields that are induced by the reaction of electropositive rare-earth metal alloys with water (Kaimmer & Stoner, 2008; Brill *et al.*, 2009; Tallack & Mandelman, 2009) and by movements through magnetic fields (Klimley, 1993; Kalmijn, 2000; Meyer *et al.*, 2005; Peters *et al.*, 2007). Hence, permanent magnets have the potential to deter sharks (Stoner & Kaimmer, 2008; Rigg *et al.*, 2009; O'Connell *et al.*, 2010, 2011*a*). The effect of permanent magnets and electropositive metal alloys on the behaviour and bycatch of sharks has been assessed recently in a range of species, but much variation between species, studies, life stages and magnets/metals has been observed (Table I). More research to assess the repulsive effect of magnetic repellents on the behaviour of sharks is therefore necessary.

The sandbar shark, *Carcharhinus plumbeus* (Nardo, 1827) is a member of the family Carcharhinidae and is closely related to several species that are vulnerable to long-line fisheries (Mandelman *et al.*, 2008; O'Connell *et al.*, 2014*c*). Previous studies on *C. plumbeus* elicited negative responses from juveniles on electropositive metal repellents (Brill *et al.*, 2009), but the possible repulsive effect of permanent magnetic fields on the behaviour of adult *C. plumbeus* still has to be demonstrated (O'Connell *et al.*, 2011*b*; Hutchinson *et al.*, 2012). Hutchinson *et al.* (2012) suggested that the absence of a response in marine trials could be due to a particular feeding strategy, or to different sensory modalities. The latter was tested in an experimental environment and it was predicted that captive adult *C. plumbeus* conditioned to associate a target with food will be more reluctant to approach that target when it is fitted with a permanent magnet.

MATERIALS AND METHODS

STUDY ANIMALS AND EXPERIMENTAL DESIGN

Experiments were carried out with three captive adult *C. plumbeus* (160-180 cm total length) at Rotterdam Zoo in the Netherlands. These *C. plumbeus* were caught as neonates along the Florida coastline and transported to Rotterdam Zoo as part of a permanent exhibition. The animals were kept and experiments conducted in this public aquarium (30 x 25 x 5.5 m). The natural seawater in the aquarium was constantly recycled and filtered. Temperature and salinity were kept constant around 25°C and 35, respectively. Also present in in the public aquarium were three other species of shark (*Carachinus acronotus* (Poey, 1860), *Carachinus limbatus* (Müller & Henle, 1839) and *Ginglystoma cirratum* (Bonnaterre, 1788)), turtles and fishes. Because of the shared “habitat”, the filtration, circulation and heating systems could not be disconnected from the aquarium during the experiments. The standard procedure at Rotterdam Zoo is to feed sharks up to 4% of their body mass four times a week. The *C. plumbeus* were conditioned to touch a target (PVC, diameter 20 cm) in return for food. After a successful hit, a sound signal rang as a positive reinforcer and food was presented to the shark at 1.5 m distance from the target (see: Clark, 1959; Wright & Jackson, 1964).

The experimental design involved three *C. plumbeus* which were individually tested (and recorded on video) in the presence or absence of a magnetic field (magnetic treatment, see below). Attachment of the magnet or sham magnet to the target was alternated per session, with three sessions per treatment. The number of approaches (steady, straight-line swimming through the water column in the direction of the target) were then recorded. Hitting the target with the anterior part of the head was scored as a successful approach. Approaching the target without physically touching the target, and/or showing clear avoidance behaviour such as a sharp turn and/or acceleration away from the target (O'Connell *et al.*, 2014*a*) was scored as an unsuccessful approach.

MAGNETIC TREATMENT

The treatment consisted of a cylindrically shaped (Ø70xh30 mm) 360 mT neodymium-iron-boron ($Nd_2Fe_{14}B$) magnet with a nickel-copper-nickel coating (Sprecher *et al.*, 2014) or a cylindrically shaped steel sham magnet (Ø70xh30 mm) being attached vertically with its top to the back side of the target. Both the magnet and sham magnet were placed inside a PVC case to prevent corrosion and obscure any visual differences between them. The thickness of the case was 4 mm at the top and bottom, and 1.8 mm at the sides. The magnetic field of the magnet inside its PVC case was measured with a Magnet-physik, Dr Steingroever GmbH, FH (http://www.magnet-physik.de/) 51Gauss/Teslameter on a 30x10 cm^2 grid (one data point per 2 cm^2) outside the aquarium. It was not possible to measure the magnetic field while the magnet was submerged. A schematic representation of the magnetic field around the neodymium magnet is shown in Fig. 1. Due to the vertical orientation of the magnet, *C. plumbeus* approaching the target were exposed to magnetic pole (50-250 mT).

DATA ANALYSES

A binomial test (2-sided) was used to analyse the differences in *C. plumbeus* response to the magnet and sham magnet in the total number of approaches and the number of successful approaches per individual *C. plumbeus*. Specimens were submitted to three trials per treatment, in which they showed a total number of 133 approaches. Eleven approaches (9% of all approaches) were excluded from further analysis because the *C. plumbeus* were not individually recognizable (due to the angle of the approach and strong similarity between the two females), when an interaction between *C. plumbeus* and other animals elicited a distinct change in the specimen's behaviour, or when the whole sequence from approaching to leaving the target area was not entirely visible to the observer.

RESULTS

The attachment of the magnet on the target had a significant effect on *C. plumbeus'* behaviour. The total number of approaches towards the target did not differ significantly between the treatments (Fig. 2, binomial test: Male 1, N = 33, $P > 0.05$; Female 1, N = 45, $P > 0.1$; Female 2, N = 65, $P > 0.1$). However, all three *C. plumbeus* showed a significantly lower number of successful approaches to the target when a magnet was attached to the target compared to when a sham magnet was attached (Fig. 2, binomial test: Male 1, N = 19, $P < 0.001$; Female 1, N = 13, $P < 0.01$; Female 2, N = 28, $P < 0.01$).

DISCUSSION

Conditioned adult *C. plumbeus* responded negatively to a strong magnetic field during direct approaches towards a permanent neodymium magnet. This result is consistent with the results of both laboratory and field experiments on juvenile *C. plumbeus* by Brill *at al.* (2009) but contrasts with findings by the results of long-line experiments on juvenile *C. plumbeus* by O'Connell *et al.* (2011*b*) and Hutchinson *et al.* (2012). According to O'Connell *et al.* (2011*b*), the fact that they only captured and tested juvenile *C. plumbeus* for a magnetic response might explain their observed lack of response to magnetic repellents. This is possibly because juvenile *C. plumbeus*' electroreception sensitivities differ from adults owing to differences in ampullary canal length. During the present study, all *C. plumbeus* were adults with full electroreception sensitivities. Hutchinson *et al.* (2012), suggested that differences in environmental conditions, especially visibility, could affect sensory modalities used by sharks. Their hypothesis that *C. plumbeus* living in clear waters are less susceptible to electropositive metals is in contrast with the results of the present study which was conducted in an aquarium with good visibility. O'Connell *et al.* (2011b) also noted that the differences between their study and the study of Brill *at al.* (2009) might be an artefact of a low sample size. With only three individuals tested, this is a recognized issue in the present study as well. In this case, all three *C. plumbeus* showed a significant negative response when approaching a permanent magnet which is in line with studies on several species within the Carcharhinidae (Table I).

In the aquarium of Rotterdam Zoo, *C. plumbeus* food intake depended on the number of times they hit the target. Consequentially, this refusal to hit the target resulted in a lower food intake. Food deprivation is an important factor known to effect electrosensory repellent success (Stoner & Kaimmer, 2008; O'Connell *et al.*, 2014*c*). Unfortunately, it should be noted that due to logical constrains of working in a zoo, no food deprivation experiments were conducted during this study. The specimens were fed following the normal procedures on the days between the experiments. Since turbidity, water temperature and salinity were virtually constant during this study, these factors were unlikely to affect the results. Moreover, no habitation effects were observed (O'Connell *et al.*, 2011*a*). The possible effect of conspecific density on the effect of the repellent (Robbins *et al.*, 2011; O'Connell *et al.*, 2014*c*) could not be tested since the *C. plumbeus* were trained to approach the target individually.

The individual responses could be evaluated by repeated trials due to the captive nature of this study. This study clearly demonstrates that captive adult *C. plumbeus* show an aversive response to a strong magnetic field at the cost of a food award. Depletion of top predator populations can seriously affect oceans all around the world through cascading effects in the food web (Springer *et al.*, 2003; Myers *et al.*, 2007), which causes unpredictable changes in the ecosystem. The use of magnetic devices to reduce shark bycatch is a promising avenue that could benefit both the ecosystems and fishermen, especially since many teleost species (but see Öhman *et al*., (2007) for several exceptions) are not repelled by these devices (Rigg *et al.*, 2009; O'Connell *et al*., 2011*b*; O'Connell & He, 2014).

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Table I. An overview of the effects of electropositive or magnetic materials on the behaviour of different shark species.

Scientific name	Common name	Wild or Captive	Life stage	Study treatment	Shark response	Reference
Alopias pelagicus (Nakamura, 1935)	Pelagic thresher shark	W	NS	Electropositive metal alloy	No response	Hutchinson *et al.* (2012)
Carcharhinus plumbeus (Nardo 1827)	Sandbar shark	C; W	Juvenile	Electropositive metal alloy	Aversion	Brill *et al.* (2009)
		W	Juvenile	Barium-ferrite magnet; Electropositive metal alloy; Rare earth magnet	No response	O'Connell *et al.* (2011*b*); Hutchinson *et al.* (2012)
		C	**Adult**	**Rare earth magnet**	**Aversion**	**Current study**
Carcharhinus acronotus (Poey, 1860)	Blacknose shark	W	NS	Barium-ferrite magnet	No response	O'Connell & He (2014)
Carcharhinus amblyrhynchos (Bleeker, 1856)	Grey reef shark	C	NS	Ferrite magnet	Aversion	Rigg *et al.* (2009)
Carcharhinus galapagensis (Snodgrass & Heller, 1905)	Galapagos shark	W	NS	Rare earth magnet	Aversion	Robbins *et al.* (2011)
		W	NS	Ferrite magnet; Electropositive metal alloy	No response	Robbins *et al.* (2011)
Carcharhinus leucas (Müller & Henle, 1839)	Bull shark	W	NS	Barium-ferrite magnet	Aversion	O'Connell *et al.* (2014*c*)
Carcharhinus limbatus (Müller & Henle, 1839)	Blacktip shark	W	Adult	Barium-ferrite magnet	Aversion	O'Connell *et al.* (2011*b*)
		W	Adult	Rare earth magnet	No response	O'Connell *et al.* (2011*b*)
Carcharhinus perezi (Poey, 1876)	Caribbean reef shark	W	NS	Barium-ferrite magnet	Aversion	O'Connell and He (2014)
Carcharhinus tilstoni (Whitley, 1950)	Australian blacktip shark	C	NS	Ferrite magnet	Aversion	Rigg *et al.* (2009)
Carcharodon carcharias (L.)	Great white shark	W	NS	Barium-ferrite magnet	Aversion	O'Connell *et al.* (2014*a*)
Galeocerdo cuvier (Péron & Lesueur, 1822)	Tiger shark	W	NS	Electropositive metal alloy	No response	Hutchinson *et al.* (2012)
Ginglymostoma cirratum (Bonnaterre, 1788)	Nurse shark	W	NS	Barium-ferrite magnet	Aversion	O'Connell *et al.* (2010); O'Connell & He (2014)
Glyphis glyphis (Müller & Henle, 1839)	Speartooth shark	C	NS	Ferrite magnet	Aversion	Rigg *et al.* (2009)
Isurus oxyrinchus (Rafinesque, 1810)	Shortfin mako	W	NS; Juvenile	Electropositive metal alloy	No response	Hutchinson *et al.* (2012); Godin *et al.* (2013)

Mustelus canis (Mitchill, 1815)	Dusky smooth-hound	W	Adult	Rare earth magnet	Aversion	O'Connell *et al.* (2011*b*)
Negaprion brevirostris (Poey, 1868)	Lemon shark	C; W	Juvenile; NS	Barium-ferrite magnet	Aversion	O'Connell *et al.* (2011*a*); O'Connell *et al.* (2014*b*); O'Connell & He (2014)
Prionace glauca (L.)	Blue shark	W	NS; Juvenile	Electropositive metal alloy	No response	Hutchinson *et al.* (2012); Godin *et al.* (2013)
Rhizoprionodon acutus (Rüppell, 1837)	Milk shark	C	NS	Ferrite magnet	Aversion	Rigg *et al.* (2009)
Rhizoprionodon terraenovae (Richardson,1836)	Atlantic sharpnose shark	W	Mixed	Rare earth magnet	Aversion	O'Connell *et al.* (2011*b*)
Scyliorhinus canicula (L.)	Small spotted catshark	C	Mixed	Rare earth magnet	Aversion	Smith & O'Connell (2014)
Sphyrna lewini (Griffith & Smith, 1834)	Scalloped hammerhead shark	C; W	NS	Ferrite magnet; Electropositive metal alloy	Aversion	Rigg *et al.* (2009); Hutchinson *et al.* (2012)
Squalus acanthias (L.)	Spiny dogfish	C; W	NS	Electropositive metal alloy	Aversion	Kaimmer & Stoner (2008); Stoner & Kaimmer (2008)
		C; W	NS; Adult	Electropositive metal alloy; Rare earth magnet	No response	Stoner & Kaimmer (2008); Tallack &Mandelman (2009); O'Connell *et al.* (2011*b*)

C: Captive; W: Wild; NS: Not specified

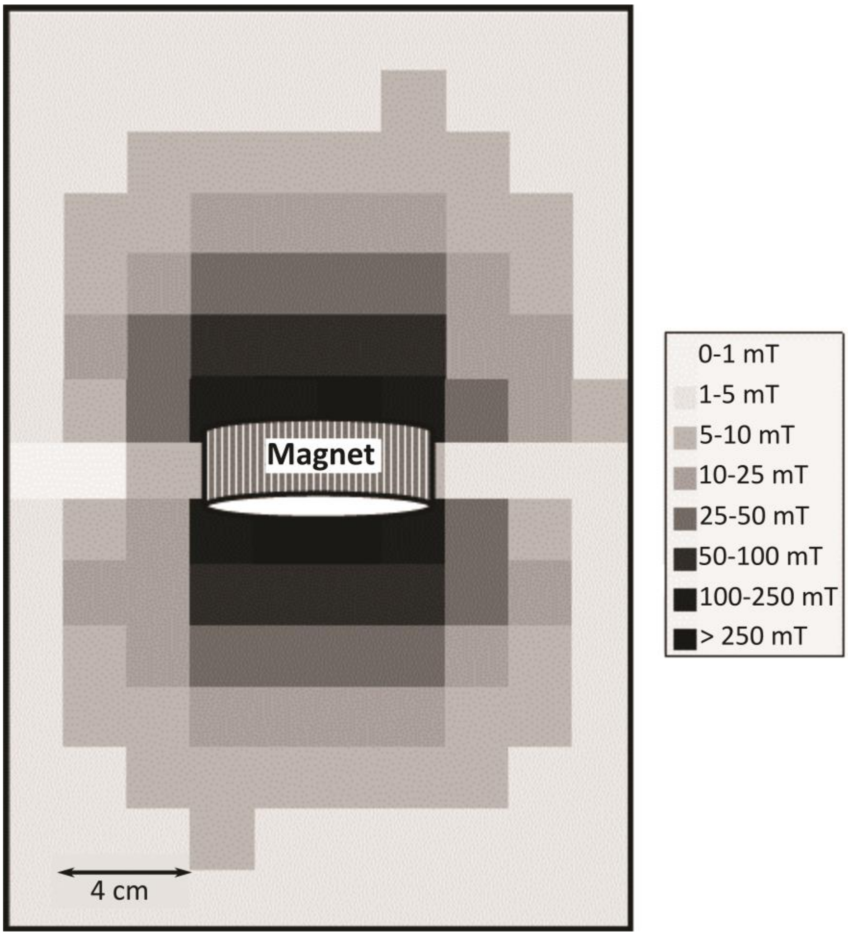

Fig. 1. Stylized spatial distribution of the magnetic field of a 70x30 mm neodymium cylinder shaped magnet. Proportions are shown to scale. Magnetic induction was measured with a Magnet-physik, Dr Steingroever GmbH, FH 51 Gauss/Teslameter. Background magnetic field was 0.3 mT.

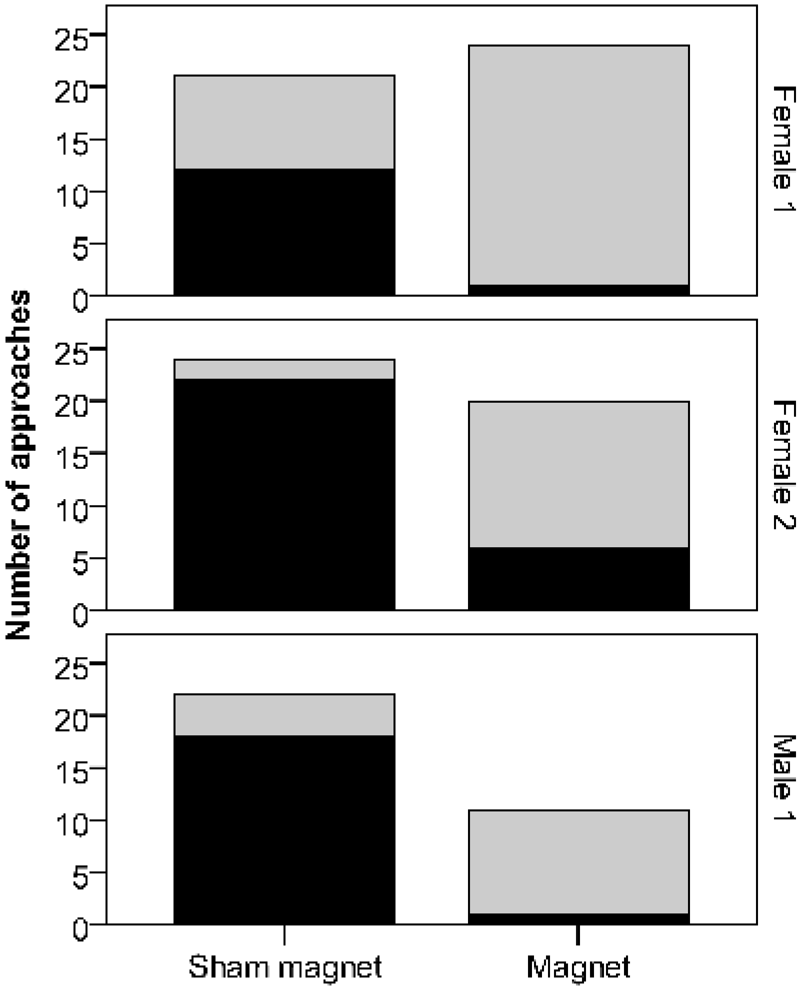

Fig. 2. Total number of approaches to the target (light bars) and the number of successful approaches to the target (dark bars) by three *C. plumbeus*. Hitting the target with the anterior part of the head was scored as a successful approach. A magnet (360 mT) or a sham magnet was attached to the target during the target training (three trails per treatment). The difference in the number of successful hits on the target between the dummy and magnet treatment was significant for all three *C. plumbeus* (Binomial test, *P*<0.01).