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The use of permanent magnets to reduce elasmobranch encounter with a simulated beach net. 2. The great white shark (*Carcharodon carcharias*)

Craig P. O'Connell [a], [*], Sara Andreotti [b], Michael Rutzen [c], Michael Meÿer [d], Pingguo He [a]

[a] School of Marine Science and Technology, University of Massachusetts Dartmouth, New Bedford, MA 02740, USA
[b] Evolutionary Genomics Group, Department of Botany and Zoology, Private Bag X1, Stellenbosch University, Stellenbosch 7600, South Africa
[c] Shark Diving Unlimited, Kleinbaai, Gansbaai 7220, South Africa
[d] Department of Environmental Affairs, Branch Oceans and Coasts, Private Bag X2, Roggebaai, Cape Town 8012, South Africa

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ABSTRACT

Beach nets are preventative devices that are utilized to minimize the potential interaction between a beachgoer and a predatory shark. One species, the great white shark (*Carcharodon carcharias*), the focal species for the present study and a protected species in South African waters, is often killed in beach nets within the KwaZulu-Natal (KZN) region. To address the issue of *C. carcharias* capture in beach nets and to reduce mortality of this species, two related experiments were carried out: the bait experiment and the magnetic-control barrier experiment. Both experiments were aimed to determine the effect of permanent magnets on *C. carcharias*. During the bait experiment, a total of twenty *C. carcharias* interacted with the control and magnetic apparatuses. The results indicate that avoidance and feeding behaviors were significantly associated with treatment type, suggesting that permanent magnets had *C. carcharias* deterrent capabilities. In addition, it was demonstrated that the likelihood of an avoidance behavior on the magnet-associated baits was not significantly correlated with water visibility or conspecific density. For the second experiment, results from stage I of the magnetic-control barrier experiment indicate that behavior was not associated with treatment zone; however, stage II indicated that behavior was significantly associated with treatment type. Results from the magnetic-control barrier experiment clearly demonstrate that although a visual barrier, such as the procedural control barrier, may be sufficient to deter *C. carcharias* from an area, the addition of permanent magnets provide additional successful deterrence of *C. carcharias*. This study demonstrates that *C. carcharias* are sensitive to strong permanent magnetic fields; therefore a large-scale experiment with a substantially greater sample size is warranted to investigate the potential of a non-invasive magnetic barrier to replace detrimental beach nets in KwaZulu-Natal, South Africa.

1. Introduction

The great white shark (*Carcharodon carcharias*) is an apex predator that has a global distribution in both temperate and tropical seas. *C. carcharias* is characterized by having a wide but selective dietary preference which ranges from vertebrates (e.g. marine mammals, teleosts, other elasmobranchs, chelonians) to invertebrates (e.g. cephalopods) (Casey and Pratt, 1985; Cliff et al., 1989; Compagno, 1984; Fergusson, 1996; Fergusson et al., 2000; Klimley, 1985; Martin et al., 2005; Tricas and McCosker, 1984). However, due to their large size and substantial geographic ranges, considerable challenges exist in obtaining behavioral and/or ecological data on *C. carcharias*, thus making it difficult to accurately assess their population status.

Exploitation of this species is concerning, due to its k-selected nature (Calliet et al., 1985; Compagno, 2001; Pratt, 1996; Watts, 2001). *C. carcharias* is characterized by having low fecundity, producing an average of 2–14 pups per litter (Francis, 1996; Saidi et al., 2005; Uchida et al., 1996), slow growth (Wintner and Cliff, 1999), and late sexual maturity which is estimated to be ≥380 cm total length (TL) for males and ≥450 cm TL for females (Hubbell, 1996). Due to its low rebound potential and current estimated stock status, *C. carcharias* is listed as vulnerable (Fergusson et al., 2009) according to the IUCN (International Union for the Conservation of Nature) Red List. Additionally, *C. carcharias* was listed in the CITES (Convention of the International Trade in

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[*] Corresponding author.
E-mail address: coconnell2@umassd.edu (C.P. O'Connell).

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Endangered Species of Wild Flora and Fauna) Appendix II in 2005 as a means to prevent utilization/exploitation which is incompatible with their survival.

Despite *C. carcharias* receiving international attention due to their inherent susceptibility to being overexploited and the black market trade for their jaws, teeth and fins (Compagno et al., 1997; Compagno, 2001), each year many great white sharks are killed by a variety of anthropogenic activities, including beach nets (Cliff et al., 1989). Beach nets are devices used to minimize the potential interaction between several predatory shark species (e.g. *C. carcharias*, tiger shark-*Galeocerdo cuvier*, and bull shark-*Carcharhinus leucas*) and beachgoers (Cliff and Dudley, 1992; Dudley, 1997). Currently, three major beach net programs exist: (1) New South Wales, Australia (Hamer, 1993), (2) Queensland, Australia (Anon, 1998), and (3) KwaZulu-Natal, South Africa (Dudley, 1997; Dudley and Gribble, 1999; Dudley and Simpfendorfer, 2006; Hamer, 1993), with each program differing in beach net length, duration of deployment and depth of net (Dudley, 1997). Since the present study was conducted in South African waters, the catch associated with beach nets from KwaZulu-Natal is most relevant. In the KwaZulu-Natal region, between 1978 and 2008, approximately 33,684 large sharks were caught by the nets, of which 12.5% were released alive. Specifically, between 1978 and 2008 approximately 1063 great white sharks (*C. carcharias*), 1528 tiger sharks (*G. cuvier*), 6610 hammerhead sharks (*Sphyrna lewini*, *S. zigaema* and *Sphyrna mokarran*), 26 whale sharks (*Rhincodon typus*) and 1580 manta rays (*Manta birostris*) were entangled in the nets (Peschak, 2009). Unfortunately these nets are not species-selective. As a result, a variety of other marine animals such as turtles, whales, dolphins, rays, manta rays, and harmless species of sharks are entangled and killed.

Conservation efforts are pertinent to the survival of a variety of elasmobranch species, especially *C. carcharias*. One particular approach to reducing elasmobranch mortality in fisheries (Kaimmer and Stoner, 2008; Rigg et al., 2009; O'Connell et al., 2011b) and beach nets (O'Connell et al., 2011a; O'Connell et al. Submitted for publication), is the use of electrosensory stimuli (e.g. permanent or rare-earth magnets and/or electropositive metals) to overstimulate the acute electrosensory system, known as the ampullae of Lorenzini, of an approaching elasmobranch. It is hypothesized and evidenced by numerous field and laboratory experiments that the presence of magnets induce elasmobranch-associated deterrent responses and suggests that the use of electrosensory materials have the potenetial to reduce the directed elasmobranch capture in beach nets (O'Connell et al., 2011a; O'Connell et al. Submitted for publication) and elasmobranch bycatch in both recreational and commercial fisheries (Rigg et al., 2009; O'Connell et al., 2011b).

With varying successes in the elasmobranch deterrent capabilities of magnets when applied to hooks in recreational and commercial fishing-related studies (O'Connell et al., 2011b; Robbins et al., 2011), the present study aims to further examine the beach net exclusion capabilities of barium-ferrite ($BaFe_{12}O_{19}$) permanent magnets, by analyzing the behavioral interactions of *C. carcharias* towards magnets in two experiments. For the first experiment, the bait experiment, the feeding behavior of *C. carcharias* towards control and magnetic-treated baits was assessed to determine the deterrent capability of permanent magnets on *C. carcharias*. It was hypothesized that due to the strength of the magnetic field ($\sim$1000 G) in comparison to the Earth's geomagnetic field (0.25–0.65 G), the electrosensory system of approaching *C. carcharias* would be overstimulated, thus resulting in a significantly greater frequency of avoidances towards the magnetic-treated bait, and a significantly greater number of feedings on the control-treated bait. For the second experiment, the magnetic-control barrier experiment, the swimming behavior of *C. carcharias* was assessed in response to permanent magnets suspended through the water column. It was hypothesized that interacting sharks will avoid the magnetic region of the barrier in comparison to procedural control and control barriers, and enter the procedural control and control barriers at a greater frequency. Additionally, assessements were also made to determine how environmental (e.g. salinity, turbidity, and water visibility) and biological (e.g. conspecific density) parameters may alter deterrent success. It was hypothesized that due to intra-specific competition (Polis, 1981) and social facilitation (Guttridge et al., 2009), high conspecific density would reduce repellent success. Secondly, increased turbidity and low water visibility conditions may reduce the visual capabilities of *C. carcharias* and therefore *C. carcharias* may rely more heavily on other senses, such as electroreception for routine activities such as prey capture. Therefore decreased water visibility and increased turbidity may increase repellent success. Lastly, due to the low resistivity of lower salinity waters, the mechanisms behind geomagnetic field detection in elasmobranchs (Kalmijn, 1982, 1997; Montgomery and Walker, 2001) are suggested to be problematic (Kalmijn, 1984). It is therefore hypothesized that higher salinity conditions may yield a greater electromotive field (with current velocity being constant at study location) and therefore be more likely to deter *C. carcharias* from both baits and the magnetic control barrier.

This paper is the second in a series of four describing the effects of permanent magnets on elasmobranch species that are frequently captured in beach nets. The remaining papers in this series will explore the effects of permanent magnets on other elasmobranch species frequently entangled in beach nets, including the great hammerhead shark (*S. mokarran*) and tiger shark (*G. cuvier*).

2. Methods

This study was conducted in December 2011 near the Dyer Island Nature Reserve (Kleinbaai, Gansbaai, South Africa). All research was conducted and abided to the rules and regulations of the assigned South African Department of Environmental Affairs research (RES2011/50) and the Department of Agriculture, Forestry and Fisheries Dive Ban (1111632) permits. The Dyer Island Nature Reserve (34°41′S; 19°25′E) includes two islands (Dyer Island and Geyser Rock) and is characterized by strong currents, large populations of seabirds, and an estimated population of 48,000 Cape fur seals (*Arctocephalus pusillus pusillus*). Research was conducted over fourteen days aboard Stan, a 9 m research vessel provided by Shark Diving Unlimited. Two different experiments were conducted: (1) The bait experiment and (2) The magnetic-control barrier experiment.

2.1. The bait experiment

For this experiment, two treatments (control and magnetic) were simultaneously deployed from the stern of the research vessel (Fig. 1a). The control comprised of bait (e.g. a 0.45–0.90 kg yellowtail (*Seriola lalandi*) head) and a 15.24 × 10.16 × 10.16 cm clay brick (sham magnet). The magnetic treatment was composed of a barium-ferrite ($BaFe_{12}O_{19}$) permanent magnet (15.24 × 10.16 × 10.16 cm) and bait. For both treatments, bait was identical in species, shape and size in order to eliminate preference-based behaviors. Bait was attached to one end of a 2 m, 1.27 cm (outer diameter) piece of PVC, with an HD GoPro 1080p video camera on the opposite end (Fig. 1b). To suspend both the camera and the bait evenly at the same depth, two 30.48 cm (outer diameter) polyform buoys were placed on either end of the PVC piping. Additionally, bait was attached to the PVC piping using

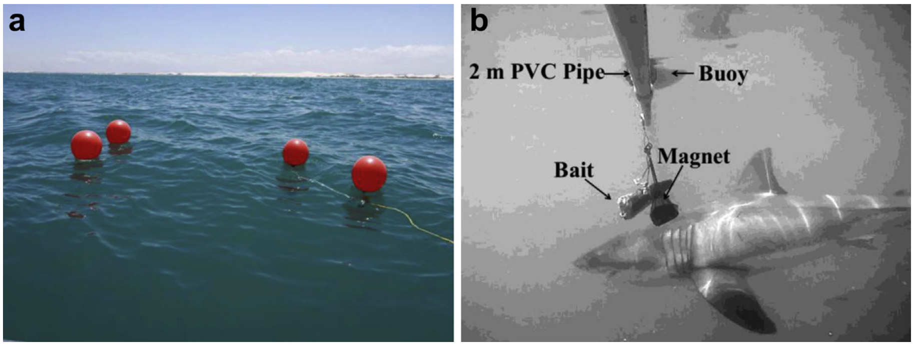

Fig. 1. a) Topside view of the bait experiment. Each set of buoys represents an experimental treatment (e.g. control or magnetic). b) Side profile of the magnetic treatment apparatus.

a monofilament nylon line which allowed for easy detachment as a shark fed on the baits. To reduce the possibility of biting the control and magnetic treatments, sham magnets and permanent magnets were attached adjacent to the bait using a separate piece of nylon rope.

To attract *C. carcharias* to the baits, additional olfactory and gustatory cues produced by a natural fish chum were used. For each trial, both the control and magnetic treatments were lowered into the water adjacent to the research vessel. The placement of each treatment in relation to one another was randomized for each replicate to eliminate side-preference based results. Similar to O'Connell et al. (2010), each trial was conducted until a bait was removed with the following behaviors recorded: approaches, avoidances, feedings, and attempted bites with an abrupt and close-range flinch. Approaches were recorded when a shark swam within 1 m of a particular treatment. Avoidance behaviors were recorded when a 45°, 90°, 180° turn, and/or an acceleration away from a treatment was observed. A feeding behavior was recorded when a bait was bitten by an approaching shark. The treatment associated with the feeding behavior was recorded even if bait was only partially removed and both treatments were retrieved and re-baited to eliminate for subsequent preference-based behaviors. Lastly, an attempted bite with an abrupt and close-range flinch was recorded when a shark was observed to approach, open its jaws within 1 m of the bait and veer away prior to making any contact with the bait or treatment. High-Definition GoPro 1080p cameras were used to permit accurate data analysis in conditions where water visibility hindered surface observations and also permit the identification of behaviors that are associated with a particular treatment. Experiments were conducted over eight days to minimize the chances of obtaining multiple replicates from the same shark. To quantify the number of sharks interacting with the experimental apparatuses and accurately assign behaviors to interacting sharks, each shark was identified using a dorsal fin identification technique (Anderson and Goldman, 1996; Gubili et al., 2009; Chapple et al., 2011; Anderson et al., 2011; Andreotti et al., submitted for publication).

2.2. The magnetic-control barrier experiment

This experiment consisted of two different stages, each of which was conducted over a period to three days. For both stages, a 1.27 cm diameter nylon rope (mainline) was deployed and suspended at the surface using nine polyform buoys. At each end of the mainline, one cinderblock, or cement block, was deployed to successfully secure each end of the mainline to the substrate. For stage I, hanging vertically in the water column was six total experimental columns, three procedural control and three magnetic columns, each having a length of 3.048 m. Three magnetic columns were deployed side-by-side, adjacent to three procedural control columns, essentially creating two treatment regions, with treatment regions being separated by a 3.048 m plain PVC column. The spacing between each vertical column was 2 m. The columns were composed of 2.54 cm (outer diameter) PVC piping. PVC was used instead of rope to create a rigid structure which prevented possible entanglement. At 1 m intervals on each column, treatment "bags" were placed. The treatment "bags" contained the procedural control or magnetic treatments. For the procedural control treatments, black clay bricks were used, as they were identical in shape, size (15.24 × 10.16 × 10.16 cm) and color to the magnetic treatments, barium-ferrite permanent magnets.

For stage II, three different treatment zones were deployed: (1) control (C), (2) procedural control (PC) and (3) magnetic (M). The procedural control and magnetic regions were identical to the regions in the first stage. The control region consisted of just surface buoys without vertical columns and was used to determine if the presence of a vertical structure (e.g. vertical columns) impacted the behavior of interacting *C carcharias*. The location of each treatment zone (e.g. control, procedural control, or magnetic treatment) was randomized to eliminate side-preference based behavior.

Once the experimental barrier was constructed, the research vessel was strategically placed upcurrent from the barrier and olfactory and gustatory cues were produced by deploying natural fish chum to attract *C. carcharias* towards the barrier. Size and unique markings (e.g. bites, scares, pigmentation) were recorded for each interacting shark, where size was estimated using the vessel as a reference. Four key behaviors were recorded during experimentation: approach, entrance, avoidance, and pass around. Approaches were recorded when a shark swam within 1 m of a particular treatment. An entrance was recorded when the shark swim between experimental columns. Avoidance behaviors were recorded when a 45°, 90°, 180° turn, and/or an acceleration away from a treatment was observed. A pass around behavior was recorded when a shark was observed to swim within 1 m of a treatment; however, swam along the perimeter of the barrier rather than entering or avoiding the area. Behaviors which occurred between the treatment separation zone column and the adjacent magnetic treatment column were not used in statistical analysis since a 1.5 m magnetic field gap existed between these regions making it difficult to assess whether or not behaviors occurring in this region were magnetically influenced (Fig. 2). Similarly, behaviors which occurred between the treatment separation zone column and an adjacent procedural control column were not used in statistical analysis as a means to standardize the locations of recordable behaviors, for both regions. All underwater behavioral interactions were filmed with the use of HD GoPro 1080p cameras

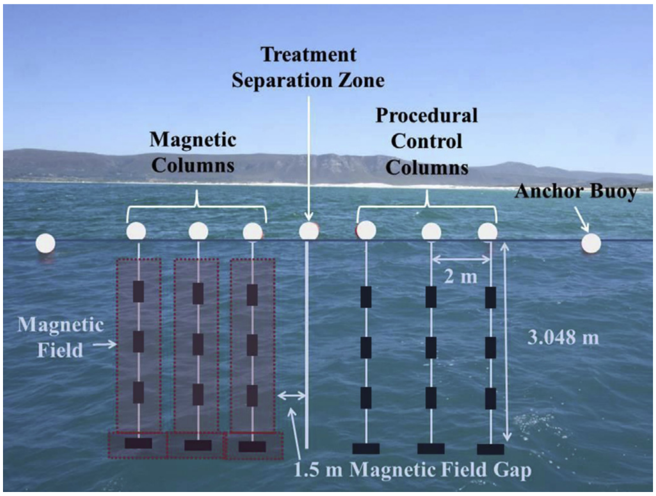

Fig. 2. Side profile of the procedural control and magnetic columns of the magnetic-control barrier used in stage I (not drawn to scale). The extent of the magnetic fields associated with the magnetic columns is highlighted by the rectangular boxes. A magnetic field gap existed between the treatment separation zone and the adjacent magnetic column and therefore behaviors associated with this region were not used in statistical analysis.

to help validate topside observations, in addition to being used to identify individual sharks using unique individual marks and their dorsal fins (that did not break the sea surface). Similar to the bait experiment, dorsal fin photo identification techniques were used to identify each interacting shark (Anderson and Goldman, 1996; Gubili et al., 2009; Chapple et al., 2011; Anderson et al., 2011; Andreotti et al., submitted for publication).

3. Statistical analyses

3.1. The bait experiment

To determine if the behavior of *C. carcharias* was associated with a particular treatment, chi-square (χ^2) analyses were used. To determine if any treatment preferences existed, a chi-square analysis was used to compare the number of visits to each treatment side. For this analysis, only the first visit of each interacting shark was recorded, since subsequent visits may be influenced by previous interactions. If no association between visits and treatment type existed, chi-square analyses were conducted for the initial interaction (visit + avoidance or visit + feeding) of each shark towards both the control and treatment baits, with initial visits not associated with a secondary behavior (e.g. avoidance or bite) being excluded from analysis. Additionally, a separate chi-square analysis was conducted on total avoidance and feeding behaviors. Analyzing the data in this fashion is pertinent due to the fact that one must also know how *C. carcharias* responds to these deterrents on a repeated interaction basis. Total avoidance and feeding behaviors were analyzed together since the data for each behavior type were not collected independently. The chi-square analysis did not incorporate attempted bites with an abrupt and close-range flinch due to a small number of such behaviors observed.

3.2. The magnetic-control barrier experiment

Since the dorsal fins of interacting sharks rarely penetrated the sea surface prohibiting individual shark identification during this experiment, researchers could not conduct an accurate statistical test to determine if any treatment preferences existed based on initial visits; however, chi-square analyses were used for both stage I and II of experimentation to determine if any associations existed between treatment type and behavior (e.g. avoidance, pass around, and entrance behaviors). First, chi-square analyses were conducted for the initial interaction (visit + avoidance, visit + entrance, or visit + pass around) of each shark towards each treatment zone, with initial visits not associated with a secondary behavior (e.g. avoidance, pass around, or entrance) being excluded from analysis. Secondly, to determine the overall impact of the magnets, total avoidance, pass around, and entrance behaviors were analyzed together since the data for each behavior type were not collected independently. Lastly, three different comparisons between treatment type were made: (1) C-PC, (2) PC-M, and (3) C-M, using chi-square analyses as a means to determine the true effect of the magnetic treatments on shark behavior.

3.3. Additional experimental observations

In addition to the basic behavioral observations, researchers also recorded a variety of environmental and biological variables to determine their potential impact on deterrent success.

3.4. Turbidity, salinity, and water visibility

Prior to each at-sea trial, salinity, water visibility and turbidity measurements were recorded, and after each trial, turbidity measurements were also recorded. Salinity measurements were made using an Extech EC400 Meter. To measure turbidity, researchers first obtained a water sample by using a 1.5 L Science Source Economy Water Sampler. Water was placed in a 50 mL centrifuge tube and turbidity measurements were obtained once back on land using a HACH 2100Q Portable Turbidimeter. Water visibility measurements were made using a secchi disk. Salinity and turbidity did not change throughout experimentation and therefore were not used as a predictor variable for chi-square or likelihood analyses. Once experimentation concluded, the behavior of *C. carcharias* was placed in the appropriate water visibility categories – (1) low: $\leq$3.5 m and (2) high: $>$3.5 m. After data was appropriately categorized a multi-dimensional chi-square analysis was then conducted to determine if there were any associations between the water visibility, treatment type and *C. carcharias* behavior. Also, to determine if feeding or entrance behaviors by *C. carcharias* towards or through the magnetic treatments were influenced by water visibility, a two sample *Z*-test which compares the appropriate data from the two categories was used.

3.5. Conspecific density

During each trial, researchers recorded the number of sharks which were observed at the sea surface and within approximately 10 m of the experimental apparatuses. At the conclusion of experimentation, behaviors such as avoidances, feedings, entrances, and passes around were separated into two categories: (1) when only one shark is interacting and (2) when greater than one shark is interacting. Multi-dimensional chi-square analyses were then used to determine if there were any associations between conspecific density, behavior, and treatment type. To determine if avoidance, feeding, entrance or pass around behaviors towards or through magnetic treatments were influenced by conspecific density, a two sample *Z*-test which compares the appropriate data from the two categories was used.

4. Photo identification technique

As a shark approached during either experiment and the dorsal fin was fully out of the water, not bent, perpendicular to the sea-surface and camera, and only when the animal passed directly in front of the camera lens, high resolution photographs of the dorsal fin were taken using a Canon 7D. When possible, photos were taken of both sides of the dorsal fin and both the time and location the photo was taken were recorded so each shark could be easily matched up with the appropriate behavioral observations.

Similar to previous photo identification studies (Anderson and Goldman, 1996; Chapple et al., 2011; Anderson et al., 2011; Andreotti et al., submitted for publication) each photograph was placed into a database of photos; however, due to the brevity of the present study, shark sightings were arranged by day. Using Adobe Photoshop CS5.1, each photo was cropped so the tip and base of the dorsal fin extended through the entire height of the frame. Once cropped, a standardized grid was overlain (Fig. 3a). Once in position, a trained researcher would identify distinct notches existed within each section, forming a three-number code (Fig. 3b) (e.g. the Rutzen Method in Andreotti et al., submitted for publication). For example, if the top section had two notches, the middle section had five notches, and the base section had 4 notches, the code would be 2-5-4. Researchers would then use this code to quickly search through the database to determine if the shark was a new or previously sighted individual. If, due to low quality photographs, it was difficult to determine differences between dorsal fins based on the notch technique, for the short timeframe of the current study, researchers were then permitted to use less durable distinctive characteristics, such as pigmentation patterns and/or scars.

5. Results

5.1. The bait experiment

After eight days of experimentation, we had a total of twenty different *C. carcharias* that interacted with the experimental apparatuses. All sharks were accurately distinguished using distinctive dorsal fin notches, scars, and localized spots of dark pigmentation. Using the vessel as a comparative measurement tool, it was estimated that the size of interacting sharks ranged from 2 to 4 m. At the study site, mean salinity (mean ± st. dev.; 35.8‰ ± 0.39) and turbidity (2.095 NTU ± 1.03) did not change drastically and therefore were not used for analysis.

5.2. Initial behaviors

A total of 12 and 8 initial visits were recorded towards the control and magnetic treatments, respectively ($\chi^2 = 0.800$, d.f. = 1, $p = 0.3711$), illustrating that *C. carcharias* did not exhibit side preference. Upon each initial visit towards each treatment for each shark, avoidance behaviors were found to be significantly associated with treatment type (Control (C) = 1, Magnet (M) = 10; $\chi^2 = 7.364$, d.f. = 1, $p = 0.0067$); however, feeding behaviors were data deficient (C = 3, M = 0).

5.3. Total behaviors

Avoidance (C = 13, M = 32) and feeding behaviors (C = 36, M = 2) were highly associated with treatment type ($\chi^2 = 38.443$, d.f. = 3, $p < 0.0001$; Fig. 4). Additionally, although a small number did not warrant a statistical analysis, attempted bites with an abrupt and close-range flinch (C = 0, M = 4) differed among treatments.

5.4. Conspecific density

When there was only one shark within the observation zone, avoidance (C = 3, M = 10) and feeding (C = 6, M = 2) behaviors were associated with treatment type ($\chi^2 = 5.789$, d.f. = 3, $p = 0.1234$), but not statistically significant due to a small sample size. When multiple sharks, up to five sharks at any one time, were interacting, avoidance (C = 10, M = 22) and feeding (C = 30, M = 0) behaviors were also highly associated with treatment type ($\chi^2 = 34.500$, d.f. = 3, $p < 0.0001$) and the differences were statistically different.

When comparing density categories, it was determined that when multiple sharks were interacting, *C. carcharias* was not more likely to avoid the magnetic treatments ($Z = 1.079$, $p = 0.2806$). Data could not be statistically computed for feeding behaviors, since only two feeding behaviors occurred throughout experimentation.

5.5. Water visibility

Mean water visibility (mean ± st. dev.) was 5.04 m ± 1.9. When visibility was less than 3.5 m, avoidance (C = 6, M = 16) and feeding (C = 21, M = 0) behaviors were significantly associated with treatment type ($\chi^2 = 25.545$, d.f. = 3, $p < 0.0001$). A similar correlation existed when visibility was greater than or equal to 3.5 m with avoidance (C = 7, M = 16) and feeding (C = 15, M = 2) behaviors being significantly associated with treatment type ($\chi^2 = 13.463$, d.f. = 3, $p = 0.0037$).

When comparing water visibility categories, it was determined that during low visibility conditions (≤3.5 m), sharks were not more likely to avoid the magnetic treatments ($Z = 0.9462$, $p = 0.8479$). Data could not be statistically computed for feeding behaviors, since only two feeding behaviors occurred throughout experimentation.

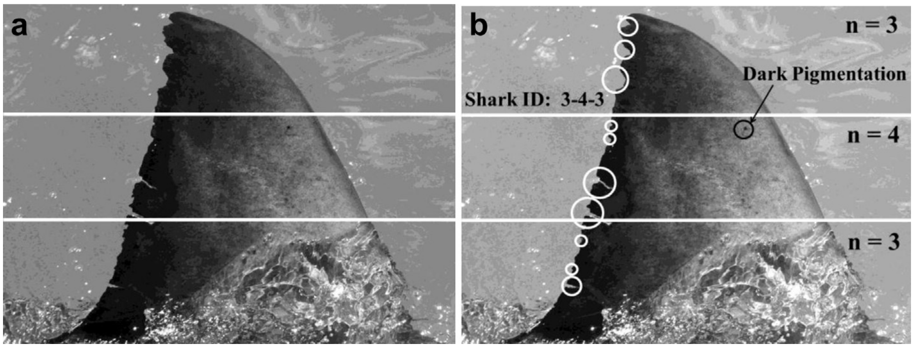

Fig. 3. a) A dorsal fin photo from *C. carcharias* which has been appropriately fitted to the Adobe Photoshop CS5.1 frame and layered with the standardized grid. b) The results from the dorsal fin photo identification technique (e.g. the Rutzen Method in Andreotti et al., submitted for publication) which highlights some of the key distinctive features of the dorsal fin, including notches and dark pigmentation. The identification code obtained from this fin was 3-4-3.

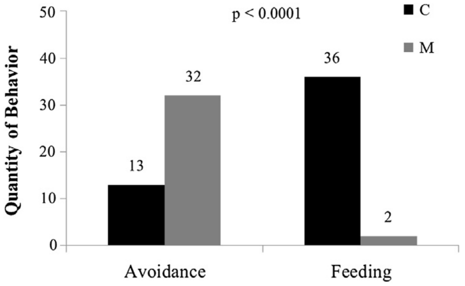

Fig. 4. The total avoidance and feeding behaviors of twenty different great white sharks (*Carcharodon carcharias*) during the bait experiment.

5.6. The magnetic-control barrier experiment

This study was conducted over the course of six days, with three days allotted to each stage of experimentation. For stage I, researchers were able to identify a total of eight distinct sharks; however, there was potential for a total of eleven, as three could not be accurately identified. Sharks ranged in size from 1.5 to 4.2 m. For stage II, researchers successfully identified six distinct sharks, and potentially up to ten, as four could not be successfully identified. Sharks from stage II ranged in size from 1.3 to 3 m.

Research from stage I demonstrated that upon each initial visit towards each treatment zone for each shark, avoidance behaviors (Procedural Control (PC) = 0, Magnet (M) = 3) and entrance behaviors (PC = 2, M = 0) were data deficient; however, pass around behaviors were not significantly associated with treatment type (PC = 8, M = 6; $\chi^2 = 0.286$, d.f. = 1, $p = 0.5930$). Total avoidance (Procedural Control (PC) = 3, Magnet (M) = 8), entrance (PC = 6, M = 1), and pass around (PC = 30, M = 31) behaviors were not significantly associated with treatment type ($\chi^2 = 5.861$, d.f. = 5, $p = 0.3200$; Fig. 5a). Additionally, the largest *C. carcharias* (4.2 m) was observed to easily pass through the procedural control columns. This observation served as a clear indication that the 2 m spacing between vertical columns was appropriate in permitting entrances for sharks of at least 4.2 m or less.

Research from stage II demonstrated that upon each initial visit towards each treatment zone for each shark, avoidance behaviors (Control (C) = 0, PC = 0, M = 6; $\chi^2 = 12.00$, d.f. = 2, $p = 0.0025$), entrance behaviors (C = 9, PC = 2, M = 0; $\chi^2 = 12.194$, d.f. = 2, $p = 0.0022$), and pass around behaviors (C = 0, PC = 8, M = 3; $\chi^2 = 8.918$, d.f. = 2, $p = 0.0116$) were significantly associated with treatment type. Total avoidance (C = 1, PC = 2, M = 12), entrance (C = 45, PC = 15, M = 3), and pass around (C = 7, PC = 38, M = 36) behaviors were significantly associated with treatment type ($\chi^2 = 81.668$, d.f. = 8, $p < 0.0001$; Fig. 5b). In addition to comparisons between all the experimental treatments, chi-square analyses for the total behaviors towards C-PC, PC-M, and C-M revealed interesting associations. For the C-PC comparison, entrance and pass around behaviors were found to be significantly associated with treatment type ($\chi^2 = 36.356$, d.f. = 3, $p < 0.0001$). Avoidance behaviors were excluded from experimental analysis since avoidance quantity was insufficient for analysis. For the PC-M and C-M comparisons, all behaviors were found to be significantly associated with treatment type (PC-M: $\chi^2 = 15.197$, d.f. = 5, $p = 0.0096$; C-M: $\chi^2 = 65.616$, d.f. = 5, $p < 0.0001$).

6. Discussion

The present study serves as a series of small-scale experiments which demonstrate that *C. carcharias* is sensitive and can be deterred by Grade C8 barium-ferrite ($BaFe_{12}O_{19}$) permanent magnets. Avoidances and lack of feeding behaviors served as indicators that permanent magnets had *C. carcharias* deterrent capabilities. In addition, a greater quantity of attempted bites with an abrupt and close-range flinch was observed towards the magnetic treatment in comparison to the control because shark approaches to the control led to bites rather than attempted bites, thus further exemplifying the deterrent capabilities of permanent magnets. Although data were limited, two sample *Z*-tests demonstrated that *C. carcharias* was not more likely to avoid the magnetic treatment bait during different water visibility or conspecific density categories. During stage I of the magnetic-control barrier experiment, no significant associations existed between treatment type and both initial and total behaviors; however, the findings from stage I suggested that the presence of a visual barrier may have sufficient deterrent capabilities. Stage II of experimentation demonstrated that initial and total behavior was significantly associated with treatment type. Additionally, when analyzing how *C. carcharias* interacted towards the: (1) C-PC, (2) PC-M, and (3) C-M barriers, all relationships were found to be significant. Results from stage II revealed that although the presence of a visual barrier (e.g. procedural control columns) have deterrent capabilities, the addition of permanent magnets have a significantly higher deterrent capacity and therefore are necessary to maximize the effectiveness of future *C. carcharias* exclusion barriers.

6.1. Biological and environmental parameters

Although attempts were made to determine the influence of biological and environmental parameters on *C. carcharias*, due to the short-term duration of this experiment, the key environmental parameters (e.g. salinity and turbidity) did not change drastically to allow for any comparative analyses for the bait experiment. Similarly, for the magnetic-control barrier experiment, there was also no substantial change in salinity or turbidity which prevented any

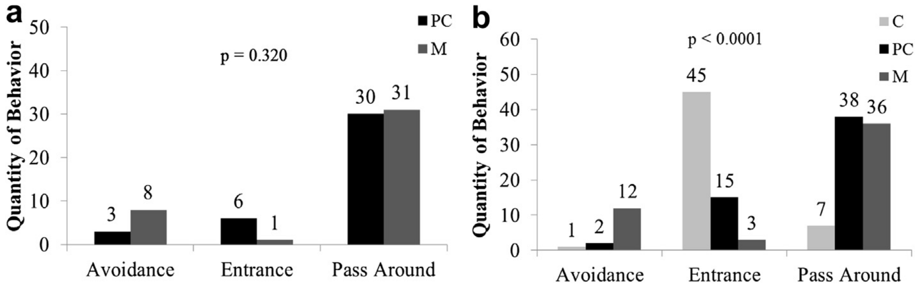

Fig. 5. Behaviors associated with the magnetic-control barrier experiment. a) The total avoidance, entrance and pass around behaviors of eight (potentially eleven) different great white sharks (*Carcharodon carcharias*) during stage I towards the procedural control (PC) and magnetic (M) treatments. b) The total avoidance, entrance and pass around behaviors of six (potentially ten) different *C. carcharias* during stage II towards the control (C), procedural control (PC) and magnetic (M) treatments.

further statistical analyses. For the remaining parameters during the magnetic-control barrier experiment, such as water visibility and conspecific density, all behaviors occurred within one category of each parameter, thus also preventing any comparative analyses.

6.2. The bait experiment

For the bait experiment, neither conspecific density nor water visibility were demonstrated to have any impact on the deterrent capabilities of permanent magnets on *C. carcharias*; however, these results may be due to low sample size. Previous studies which aimed to determine the impact of conspecific density on the deterrent capabilities of electrosensory stimuli have produced mixed results (Tallack and Mandelman, 2009; Robbins et al., 2011; O'Connell et al. submitted). For example, Tallack and Mandelman (2009) examined the effects of electropositive metals on the behavior of the spiny dogfish (*Squalus acanthias*) and found that repellent effectiveness was not correlated to conspecific density. In contrast, O'Connell et al. (Submitted for publication) deployed a magnetic-control barrier and found that bull sharks (*C. leucas*) were significantly more likely to enter through magnetic columns in situations of high conspecific density. Similarly, Robbins et al. (2011) conducted field experiments on the Galapagos shark (*Carcharhinus galapagensis*) and demonstrated that the effectiveness of electrosensory stimuli was inversely proportional to conspecific density. Therefore, evidence suggests that correlations between electrosensory stimuli (e.g. magnets or metals) effectiveness and conspecific density may be a species-specific phenomenon.

No change in behavior towards the magnetic treatment was observed in relation to water visibility during the bait experiment. In contrast to the present findings, O'Connell et al. (Submitted for publication) deployed a magnetic-control barrier and concluded that *C. leucas* was found to be significantly more likely to enter through magnetic columns during periods of high water clarity. Although the retina rod-to-cone ratio (4:1) in *C. leucas* (Shieber et al., 2011) is identical to *C. carcharias* (Gruber and Cohen, 1985), *C. leucas* is typically associated with highly turbid environments, thus may be better adapted at keying in on their electrosensory system when vision is compromised (e.g. sensory modulation). Similarly, it was demonstrated that blind humans showed enhanced auditory localization capabilities in comparison to sighted humans (Lessard et al., 1998; Muchnik et al., 1991; Rice, 1970). If that is the case, *C. leucas* may show a greater sensitivity to permanent magnets in low water clarity in comparison to high water clarity situations, whereas a predator such as *C. carcharias* that is highly dependent on vision for prey capture (Strong, 1996), sensitivity to electrosensory stimuli may not change with water visibility. Another potential explanation is that the water visibility categories differed between the present study and O'Connell et al. (Submitted for publication). The water visibility conditions in O'Connell et al. (Submitted for publication) ranged from 4 m to ~12 m, whereas in the present study, the water visibility ranged from 3.33 to 7.5 m, therefore, it is possible that the water visibility range in the present study was not extensive enough to induce any changes in the behavioral responses of *C. carcharias* to permanent magnetic fields.

6.3. The magnetic-control barrier experiment

In both stage I and stage II of experimentation, *C. carcharias* was observed to exhibit pass around behaviors towards the procedural control and magnetic barriers at a high frequency; however, when presented with a proper control in stage II, a high frequency of entrances were observed. One explanation as to why the swimming behavior of *C. carcharias* was significantly altered in the presence of both procedural control and magnetic columns, when compared to the control region is due to the highly developed visual system of *C. carcharias*. In comparison to other shark species, *C. carcharias* has a retinal rod to cone ratio of 4:1 (Gruber and Cohen, 1985), which results in high visual acuity and superior color vision. In addition, Strong (1996) suggested that although *C. carcharias* may utilize other senses during prey capture, the visual system plays a vital role in the ability for *C. carcharias* to locate pinnipeds at the surface. The high visual acuity and color vision, and a reliance on the visual system to locate and catch prey at the surface, may serve as potential explanations as to why the swimming behavior of interacting *C. carcharias* was significantly altered when the control was introduced in comparison to both the procedural control and magnetic barriers.

Although the presence of a visual barrier may have deterrent capabilities, factors such as light intensity (e.g. time of day and water depth), turbidity, and net color may impact visibility of a net or a barrier (Andreev, 1966; Backiel and Welcomme, 1980). Therefore even though the visual system of *C. carcharias* is highly developed (Gruber and Cohen, 1985), inshore regions where beach nets are deployed are characterized by having high turbulence and during different times of the day, low light intensity may lead to decreased visibility. Such changes in environmental condition may make the procedural control barrier nearly invisible to approaching *C. carcharias*, reducing the effectiveness of the barrier to protect a densely populated beach. While a visual barrier may play a vital role in *C. carcharias* deterrence in situations with certain environmental parameters, the magnetic field produced by the magnetic barrier targets a completely different sensory system, the ampullae of Lorenzini, and therefore provides an additional stimulus which will maximize the deterrent capabilities, as evidenced in stage II of experimentation, in low light and low visibility conditions.

7. Conclusion

Most large shark species play a top-down predatory role within their respected ecosystems. Although difficult to accurately assess, the problems stemming from the loss of apex predators can be incredibly complex and have catastrophic implications for the marine ecosystem (Baum et al., 2003; Baum and Myers, 2004; Myers et al., 2007; Ferretti et al., 2010). For example, in areas where beach nets exist in KwaZulu-Natal, South Africa, large shark populations have shown signs of decline (Holden, 1977; Dudley and Simpfendorfer, 2006). Van der Elst (1979) determined that during 1956–1976, the populations of large shark species declined (Holden, 1977), and recreational fishing data revealed that there was an abundance of two species of elasmobranchs not frequently captured within the nets (Dusky shark, *Carcharhinus obscurus* and Milk shark, *Rhizoprionodon acutus*) and a decline in teleosts. Such local ecological shifts in elasmobranch population size were suspected to be responsible for declines in target teleost populations (Van der Elst, 1979; Ferretti et al., 2010). Losing top predators within this ecosystem led to cascading trophic effects and continued fishing efforts have led to even further ecological shifts pertaining to the abundances of: (1) large predatory shark species, (2) *C. obscurus* and *R. acutus*, and (3) smaller mesopredator elasmobranchs, such as rays (Dudley and Simpfendorfer, 2006; Pradervand et al., 2007).

Due to evidence pertaining to the ecological shift in the trophic dynamics in areas associated with beach nets, new methods of bycatch reduction technology are important for the survival and rejuvenation of the marine ecosystem where these nets exist. Therefore the findings from the present study may not only aid in the local population rejuvenation of several shark species, but also help to restore the trophic dynamics in locations where beach nets currently exist. The results from this study show promise in the concept of a magnetic barrier and *C. carcharias* deterrence and due to the conservation impacts of such a technology, further investigation with a larger scope and larger sample size is warranted.

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