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Effects of the Sharksafe barrier on white shark (*Carcharodon carcharias*) behavior and its implications for future conservation technologies

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ABSTRACT

The white shark (*Carcharodon carcharias*) is an apex predator and is a protected species that suffers from several sources of anthropogenic mortality, such as shark nets. Shark nets are devices used to minimize the interaction between beachgoers and potentially dangerous sharks; however, these nets have negatively impacted local and migratory shark populations, in addition to killing substantial quantities of other marine organisms. To address this issue, the present study developed and examined the effects of an alternative technology (the "Sharksafe" barrier) composed of two stimuli: (1) visual-artificial-kelp and (2) electrosensory-magnets, on *C. carcharias* behavior. Generalized linear mixed effect models were used to test hypotheses pertaining to the effects of treatment type, exposure quantity (i.e. habituation), conspecific density, and water visibility on shark behavior. Analyses based on forty-nine, one-hour trials illustrate that the swim patterns of all sixty-three individual *C. carcharias* was altered in the presence of the artificial kelp-the procedural control region, and the magnetic kelp-the magnetic region of the barrier (i.e. procedural control and magnetic regions reduced entrance frequency and increased avoidance and pass around frequency). Also, preliminary observations illustrated that the barrier had no observable impact on Cape fur seal (*Arctocephalus pusillus pusillus*) behavior. The *C. carcharias*-specific repellency associated with the Sharksafe barrier and the ability of the barrier to withstand harsh environmental conditions warrant future experiments to assess its exclusion capabilities on predatory sharks and possible application to replace shark nets.

1. Introduction

Although rare, shark attacks have a disproportionately large impact on human behavior, often resulting in the implementation of shark culls and/or shark nets (Cliff and Dudley, 1992; Coppleson, 1962; Davies, 1964; Government of Western Australia, 2014; Wallett, 1983). With fear of attacks and increasing socio-economic pressure, shark culls are often governmental-instituted programs that involve killing sharks with the use of drum lines, or other types of baited hooks, to maximize beachgoer safety (Government of Western Australia, 2014; Ikehara, 1961; Tester, 1968, 1969). From 1959-1976, Hawaii instituted several shark control/cull programs which resulted in 4,668 shark deaths (Ikehara, 1961; Tester, 1968, 1969; Wetherbee et al., 1994). In a more recent shark culling case, Western Australia instituted 72 baited drum lines from January-April 2014 after seven fatal attacks occurred on their public beaches between 2010-2013 (Government of Western Australia, 2014; Ikehara, 1961; Tester, 1968, 1969). The guidelines required fishermen to kill and dispose of all sharks that were captured and measured to be greater than or equal to 3 m. However, due to the novelty of the Western Australian program, it is uncertain as to its overall negative impact on local shark populations. Besides the use of baited hooks, local governments have attempted to reduce the risk of shark-beachgoer interactions by implementing shark nets. Shark nets were originally instituted to catch three species of shark, the white shark (*Carcharodon carcharias*), the tiger shark (*Galeocerdo cuvier*), and the bull shark (*Carcharhinus leucas*), which were suspected as being responsible for most attacks on beachgoers (Dudley, 1997). Currently, three major shark net programs exist: (1) New South Wales, Australia (Hamer, 1993), (2) Queensland, Australia (Anon, 1998), and (3) Natal, South Africa (Dudley, 1997; Dudley and Gribble, 1999; Dudley and Simpfendorfer, 2006; Hamer, 1993). Each program uses a similarly sized mesh, ranging from 50-60 cm stretched and collectively, these nets catch a maximum of 2500 sharks per year (Dudley and Gribble, 1999). This shark mortality is justified by local governments due to increased beachgoer safety, and the direct boost of tourism prompted by these safer beach areas, which in effect creates a stable local economy

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(Dudley and Gribble, 1999). Although these nets have been shown to provide beachgoer safety (Cliff and Dudley, 1992; Green et al., 2009), these anthropogenic sources of shark mortality have had a major negative influence on local and migratory shark populations (Dudley, 1997; Dudley and Cliff, 1993).

With continued trends in elasmobranch population decline (Worm et al., 2013), there has been a drastic shift in the focus of shark repellent research, with current directions heavily focusing on the utilization of repellent technologies to minimize anthropogenic stressors on elasmobranch populations (e.g. Brill et al., 2009; O'Connell et al., 2012; Rigg et al., 2009; Robbins et al., 2011; Tallack and Mandelman, 2009). More specifically, several present and previous conservation engineering measures for the prevention of shark-beachgoer interaction include: exclusion nets, devices emitting electric fields (Cliff, 1988; Huveneers et al., 2012; Smith, 1966, 1973, 1990), and permanent magnets (O'Connell et al., 2011, 2012; Rigg et al., 2009). Exclusion nets are fine mesh nets (typically 60 mm stretched mesh) that physically exclude sharks from a bathing area. They are utilized in two countries (China and Seychelles) and are currently being trialed in Fish Hoek, South Africa (McPhee, 2012; Nel and Peschak, 2006). Current deployments in conjunction with an observer system are semi-permanent and have thus far alleviated shark-beachgoer interactions (McPhee, 2012). With little observed organismal mortality, these nets have positive environmental implications in comparison to the currently used alternatives: shark nets and drum lines. Although these nets are promising, they do have several limitations, including biological (e.g. aquatic plant debris) and environmental (e.g. wave action) conditions that impact the exclusion capabilities of the net, as well as, potential negative impacts related to coastal processes (e.g. sand transport and deposition), and potential spatial limitations associated with deployment area (Nel and Peschak, 2006). These limitations reduce the likelihood of exclusion net deployment in areas where shark nets currently exist due to the associated harsh environmental conditions and therefore, there is still a need for an alternative conservation engineering technology.

An additional means of shark-beachgoer prevention is the use of electrical devices, such as the Shark Shield™ (Huveneers et al., 2012). These devices specifically target an elasmobranchs electrosensory system, known as the ampullae of Lorenzini (Dijkgraaf and Kalmijn, 1963, 1966; cited by Kalmijn, 1971, 1982). Besides being suspected to detect geomagnetic fields (Klimley, 1993; Klimley et al., 2002), this sensory system is also sensitive to minute electric fields (Kajiura and Holland, 2002). Strong electrosensory stimuli were thus employed to overwhelm the ampullary system of sharks and to concurrently elicit repellent responses (Huveneers et al., 2012; Smith, 1966). Devices using these extrasensory stimuli were originally tested in the 1960s in South Africa to examine their utility as shark exclusion and beachgoer protection devices (Smith, 1966, 1973); however, results were not encouraging and the devices were considered prohibitively expensive (Cliff, 1988). Research on a similar concept is currently being conducted by the KwaZulu-Natal Sharks Board (KZNSB) using a shark repellent cable (SRC) - a cable that emits an electric field - to protect an entire bathing area (KZNSB, 2013).

Similar to electrical devices, permanent magnets are another potential conservation engineering measure that are suspected to target a shark's ampullary system. For example, the magnetic flux associated with grade C8 barium-ferrite ($BaFe_{12}O_{19}$) permanent magnets (~3850 G) is several orders of magnitude greater in strength than that of the Earth's magnetic field (0.25-0.65 G). It is theorized that through the process of electromagnetic induction (Kalmijn, 1973, 1982, 1984), the induced voltages are detected and are hypothesized to overstimulate the ampullae of Lorenzini of an approaching elasmobranch thus eliciting a repellent response (O'Connell et al., 2010, 2011; Rigg et al., 2009). Research on elasmobranch responses towards magnets has produced mixed results (O'Connell et al., 2012; Robbins et al., 2011); however, the use of permanent magnets to manipulate swimming patterns of interacting sharks is a promising application (O'Connell et al., 2011, 2012; Rigg et al., 2009). In a recent small-scale study, O'Connell et al. (2012) examined if permanent magnets could be utilized to manipulate swim patterns of one shark species that is often considered responsible for negative shark-beachgoer interactions, the white shark (*Carcharodon carcharias*). That study, which is referred to as Phase I of experimentation, revealed that both visual and magnetic stimuli were capable of altering shark swimming behavior. This study, or Phase II, is an advancement of Phase I and examines the potential utility of a large-scale barrier (the Sharksafe barrier), as a new and non-invasive alternative to shark nets.

Phase II employs two separate concepts. The first stems from the Phase I results (e.g. a visual stimulus can manipulate the swimming behavior of *C. carcharias*) and from the preliminary observations that demonstrate that *C. carcharias* rarely enters into a high density kelp forest even though prey species, such as the Cape fur seal (*Arctocephalus pusillus pusillus*), utilize these forests as an anti-predation strategy (Michael Rutzen pers. obs.). Secondly, Phase I data demonstrate that magnets can manipulate the swimming behavior of *C. carcharias.* Therefore, this study has two key objectives: (1) to deploy the Sharksafe barrier, which is composed of artificial kelp and permanent magnets, and (2) to examine the barrier's effect on *C. carcharias* behavior and the surrounding environment to determine if the barrier may serve as an eco-friendly alternative to shark nets. Similar to Phase I results (O'Connell et al., 2012), it was first hypothesized that both the procedural control region (e.g. artificial kelp) and magnetic region (e.g. artificial kelp and permanent magnets) would significantly alter the swimming behavior of and elicit repellent responses in *C. carcharias*. Secondly, intraspecific competition is widely reported in the animal kingdom and has been demonstrated to alter animal behavior (Brill et al., 2009; Polis, 1981; Robbins et al., 2011). Therefore, since olfactory stimuli were used to attract *C. carcharias* to the barrier, it was hypothesized that a competitive mentality would be induced and thus increases in conspecific density would result in a significant change in *C. carcharias* behavior (e.g. decreases in avoidance and pass around behaviors and increases in entrance behaviors through the treatment regions). Thirdly, elevated turbidity reduces ambient light intensity, thus impairing vision through degraded apparent contrast (Lythgoe, 1979). Relating to this concept, a previous study demonstrated how shark behavior changed towards magnetic fields with variations in visual capability (O'Connell et al., 2013a). Therefore, it was hypothesized that low visibility conditions may cause an increased reliance on electrosensory cues and thus result in a significant change in *C. carcharias* behavior towards magnetic regions (e.g. increases in avoidance and pass around behaviors and decreases in entrance behaviors) of the barrier. Fourthly, previous studies illustrate that sharks can rapidly habituate to an unchanging stimulus, such as underwater acoustics and magnetism (Myrberg et al., 1969, 1978; O'Connell et al., 2011). Due to the long-term deployment of the barrier, continuous exposure to magnetic stimuli was hypothesized to lead to habituation and therefore may result in a significant change in *C. carcharias* behavior (e.g. decreases in avoidance and pass around behaviors and increases in entrance behaviors). Lastly, to assess the overall impact of the barrier on benthic organismal growth and colonization, a basic quantitative survey was conducted. It was hypothesized that the increased surface area provided by the barrier base will yield a precipitous increase in benthic organismal colonization with time.

2. Methods

Trials were conducted throughout two, 3-month periods over two years (June-August 2012 and May-July 2013). The Dyer Island Nature Reserve (Kleinbaai, Gansbaai, South Africa; 34°41'S; 19°25'E; Fig. 1) was selected as the designated study site due to the reliable seasonal presence of *C. carcharias.* The study region is comprised of a channel between two closely associated islands, Dyer Island and Geyser Rock and is characterized by strong currents, large populations of seabirds, and an estimated population of 47,000-56,000 Cape fur seals (Kirkman et al.,

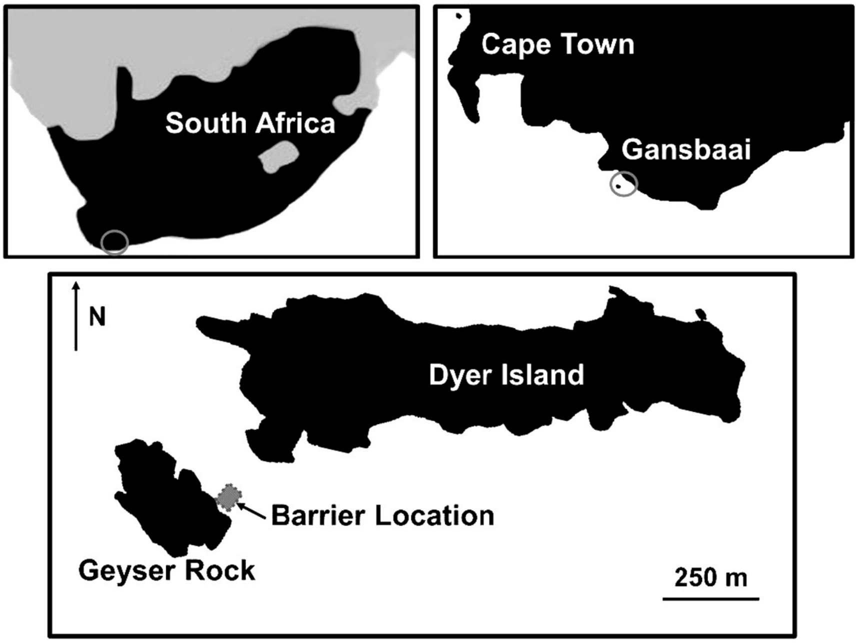

Fig. 1. Map illustrating research location within the Dyer Island Nature Reserve.

2007). Over the course of seventy-one at-sea days, the Sharksafe barrier was deployed within the channel and at a water depth of 8 m and the effects of this barrier on interacting *C. carcharias* were assessed using two research vessels provided by Shark Diving Unlimited. All research was conducted and abided to the permit conditions and regulations of the assigned South African Department of Environmental Affairs (RES2012/74 and RES2013/31) and the Department of Agriculture, Forestry and Fisheries Dive Ban (#1107689 and #1209824) permits.

2.1. Barrier Design

2.1.1. Base

To develop the barrier base, concrete blocks with centralized eye bolts were deployed in a predetermined location within the channel. Polyethylene rope threaded through the eye bolts was then used to interconnect the blocks and maximize structural integrity.

2.1.2. Barrier Elements

The barrier was composed of six regions, each of which measured 8 m: two control regions, two procedural control regions and two magnetic regions. The control consisted of an un-manipulated area (i.e. no barrier elements). The procedural control consisted of three alternating rows of rigid polyvinyl chloride (PVC) black pipes, that was used to mimic the visual appearance of sea bamboo (*Ecklonia maxima*), the kelp species that predominates the marine ecosystems around the Dyer Island Nature Reserve. The first row of the procedural control region consisted of seven, 90 mm diameter barrier elements (i.e. PVC pipe) spaced at 1 m. These 90 mm pipes were cut into two segments creating a displacement joint. These joints aided in current and wave energy displacement to maximize the structural integrity of the barrier and to ensure the barrier elements remained upright throughout deployment. The two subsequent and alternating rows consisted of thin 50 mm diameter barrier elements used to maximize the visual stimuli provided by the barrier and artificial kelp forest density. The design of the magnetic region was identical to the procedural control region; however, 15.24 cm x 10.16 cm x 2.54 cm barium ferrite ($BaFe_{12}O_{19}$) permanent magnets were placed at 1 m intervals within the 90 mm diameter PVC pipes. Once magnets were placed in the PVC pipe, each 7.5 m (length) PVC pipe was filled with high-density foam to maximize buoyancy, and connected to the eyebolt on the base using a 3.81 cm D-shackle. Once each barrier region was constructed, 50 mm diameter white PVC pipe was placed between each treatment region and served as the treatment separation zone, or an easily observable region of distinction between treatment types. Thick polyethylene rope was used to connect the barrier elements to the D-shackles in Year 1. However, consistent heavy storm and wave activity caused this rope to chafe and break after seven months of deployment and therefore, 12.7 mm galvanized chains were used on the 90 mm diameter PVC piping in Year 2 to maximize barrier longevity. Such modifications were not only beneficial to the structural integrity of the barrier, but also in limiting localized pollution associated with PVC pipe and polyethylene rope detachment from the barrier base.

2.2. Experimental Design and Sampling Technique

Treatment regions were deployed using a completely randomized experimental design (Hurlbert, 1984, Fig. 2b). For each one-hour trial, one of three observation regions that contained all three experimental treatments was randomly selected (See Fig. 2b). A vessel was then placed upstream and researchers' utilized natural fish chum to attract *C. carcharias* towards the selected observation region (Fig. 2a). When sharks or other animals approached the barrier, five key behaviors were recorded: visits, avoidances, entrances, pass arounds, and no reactions (Table 1). Behavioral interactions were filmed by an underwater camera (GoPro Hero 3 HD1080p) to help validate surface observations, and to identify individual sharks. More specifically, individual sharks were identified using a previously developed dorsal fin photo-identification technique (Anderson and Goldman, 1996; Anderson et al., 2011; Andreotti et al., 2014; Chapple et al., 2011), where possible. If the dorsal fin could not be clearly identified from the obtained footage, short term identification characteristics were used, such as: shark size, shark sex, presence/absence of a tag, shark color, pigmentation variation on the lower caudal fin (Domeier and Nasby-Lucas, 2007), presence/absence of fin damage, and presence/absence of scars. Sharks that could not be identified were excluded from Poisson regression analysis; however, the data associated with all of these sharks were aggregated and placed in an "unidentified sharks" table (Table 4).

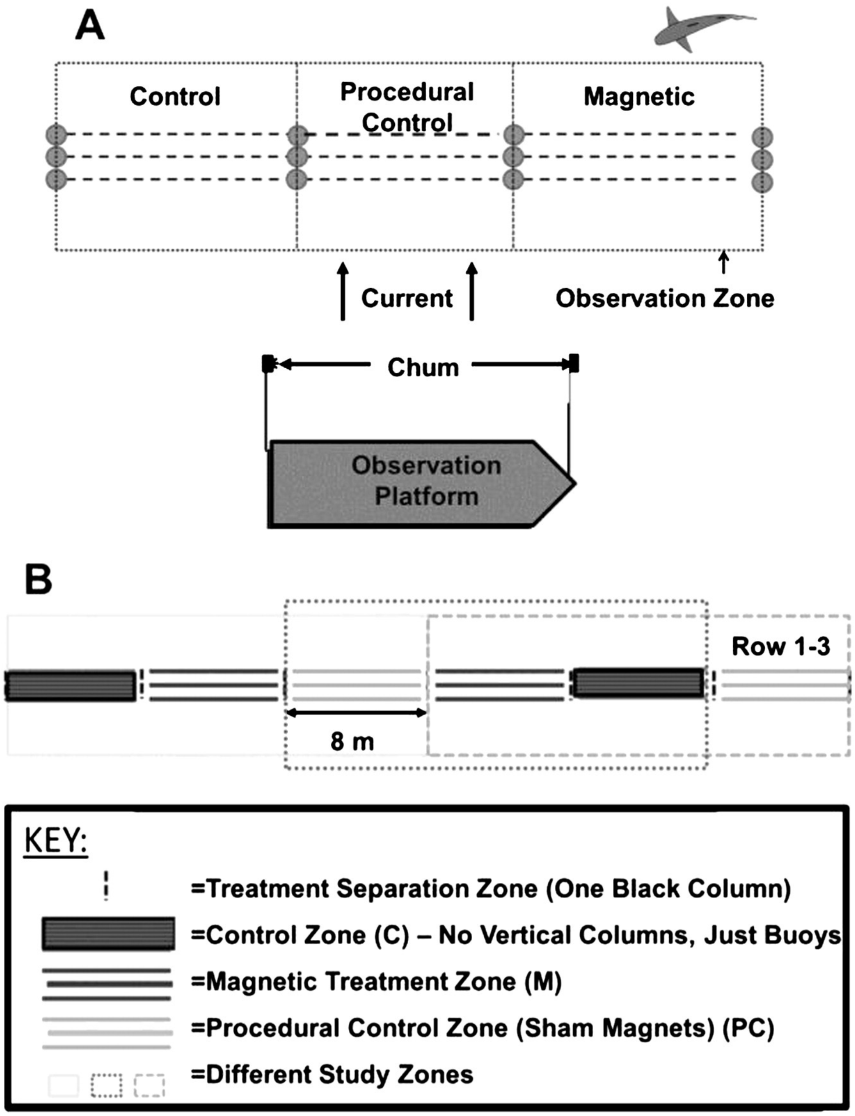

Fig. 2. Represents the experimental design used for the present study. A) Illustrates the experimental protocol used for each trial, with the research vessel (observation platform) and chum placed upstream from one study zone. B) Two replicates of each treatment zone were deployed, creating three distinct study zones.

2.3. Additional Observations

2.3.1. Explanatory Variables

Throughout the study, several variables were measured, such as: year (Y), water visibility (V), conspecific density (De), and exposure quantity (Exp), to determine their potential influence on *C. carcharias* behavior towards the barrier. The horizontal extent of water visibility was estimated using inter-column spacing as a reference or estimated using underwater observations prior to each trial. To determine conspecific density, shark quantity within visual range (~0-10 m) of the barrier was recorded during each behavioral interaction. Because many individual *C. carcharias* could be accurately identified both intra and inter-annually, exposure quantity could be determined. Individual shark exposures to each experimental apparatus were either categorized as primary (i.e. total behaviors observed from one individual shark on the first day of exposure) or secondary (i.e. total behaviors observed during all subsequent days of exposure from that same individual). After experimentation, behavioral data

Table 1
Behavioral ethogram describing the white shark (*Carcharodon carcharias*)-associated behaviors for the large-scale barrier experiment.

Behavior	Definition of Behavior
Visit	Shark swam within one body length of the barrier
Avoidances	Shark abruptly changed direction, such as a 45°, 90° or 180° turn and/or acceleration away, after visiting an observation zone
Entrances	Shark visited an observation zone and swam through the PVC pipes
Pass Around	Shark visited and swam adjacent to an entire treatment region within the observation zone
No Reaction	Shark visited an observation zone, but did not avoid, enter, or pass around

Table 2

Represents the data associated with the mixed effect models pertaining to white shark (*Carcharodon carcharias*) behavior. Individual shark (S) is treated as a random effect and the others are treated as fixed effects. These fixed variables were T (treatment), V (water visibility), De (conspecific density), and Exp (exposure quantity). For entrance frequency, data were transformed to "total entrances + 1" for each treatment region to improve the interpretability of the data, as no entrances occurred through the procedural control or magnet treatment regions throughout the entire experiment. Selected models for avoidance, entrance, and pass around frequencies were A2, B2, and C2 respectively, based on a combination of Akaike Information Criteria (AIC), and behavior of the residuals of a model using a quantile-quantile (Q-Q) plot, and associated *P*-values. Significant models for main effects ($P \le 0.05$) and interaction terms ($P \le 0.1$) are in bold.

Avoidance Frequency						
Number	Linear Form	Log Likelihood	-2(Δloglik)	ΔPAR	*P*-Value	AIC
A1	1 + S	-134.34	-	-	-	272.67
A2	**1 + S + T**	**-116.31**	**384.98**	**2**	<**0.001**	**240.62**
A3	1 + S + V	-129.81	398.48	8	0.34	279.62
A4	1 + S + De	-130.69	399.37	4	0.12	273.39
A5	1 + S + Exp	-134.18	402.85	1	0.58	274.36
A6	1 + S + T + V	-109.68	342.29	8	0.10	243.35
A7	1 + S + T + De	-112.72	345.35	4	0.13	241.45
A8	1 + S + T + Exp	-115.83	348.45	1	0.33	241.66
A9	1 + S + T + V + T*V	-104.44	323.79	12	0.57	256.87
A10	1 + S + T + De + T*De	-108.27	333.71	8	0.35	248.53
A11	1 + S + T + Exp + T*Exp	-113.87	345.52	2	0.14	241.74
Entrance Frequency						
B1	1 + S	-397.09	-	-	-	798.19
B2	**1 + S + T**	**-136.82**	**931.01**	**2**	<**0.001**	**281.64**
B3	1 + S + V	-393.69	1187.88	8	0.56	807.38
B4	1 + S + De	-395.34	1189.53	4	0.48	802.69
B5	1 + S + Exp	-396.74	1190.93	1	0.39	799.48
B6	1 + S + T + V	-133.18	406.83	8	0.50	290.36
B7	1 + S + T + De	-133.85	407.49	4	0.20	283.69
B8	1 + S + T + Exp	-136.77	410.41	1	0.74	283.53
B9	1 + S + T + V + T*V	-131.45	397.81	12	0.99	310.90
B10	1 + S + T + De + T*De	-129.29	396.98	8	0.33	290.58
B11	1 + S + T + Exp + T*Exp	-136.34	409.87	2	0.65	286.67
Pass Around Frequency						
C1	1 + S	-435.41	-	-	-	874.82
C2	**1 + S + T**	**-318.58**	**1189.39**	**2**	<**0.001**	**645.15**
C3	1 + S + V	-429.69	1300.51	8	0.18	879.39
C4	1 + S + De	-434.85	1305.67	4	0.89	881.71
C5	1 + S + Exp	-433.85	1304.66	1	0.08	873.69
C6	1 + S + T + V	-315.17	952.33	8	0.56	654.35
C7	1 + S + T + De	-318.26	955.41	4	0.96	652.52
C8	1 + S + T + Exp	-317.95	955.10	1	0.26	645.90
C9	1 + S + T + V + T*V	-308.28	938.63	12	0.31	664.56
C10	1 + S + T + De + T*De	-314.95	951.47	8	0.58	661.90
C11	1 + S + T + Exp + T*Exp	-317.58	953.48	2	0.69	649.17

Abbreviations: 1 = y-axis intercept, S = individual shark (random effect), T = treatment, V = water visibility, De = conspecific density, Exp = exposure quantity, Δloglik = change in log likelihood value between former model and model being considered, ΔPAR = change in degrees of freedom between former model and model being considered, *P*-value = indicates the level of significance of the explanatory variable added, AIC = Akaike Information Criterion (2*(log likelihood) + 2*number of parameters), a model selection criterion.

Table 3

Coefficients, standard errors, t statistic and *P*-values of explanatory variables for best models A2, B2, and C2 for avoidance, entrance, and pass around frequencies, respectively, for the white shark (*Carcharodon carcharias*) in relation to the barrier treatments. For entrance frequency, data were transformed to "total entrances + 1" for each treatment region to improve the interpretability of the data, as no entrances occurred through the procedural control and magnetic treatment zones throughout the entire experiment. Significant models for main effects ($P \le 0.05$) and interaction terms ($P \le 0.1$) are in bold.

Model	Explanatory Variable	Coefficient	Standard Error	t	*P*-value
Avoidance Frequency					
A2	**Intercept**	**-4.59**	**0.51**	**-9.08**	<**0.001**
	Magnet	**2.32**	**0.52**	**4.42**	<**0.001**
	Procedural Control	**1.36**	**0.57**	**2.37**	**0.02**
Entrance Frequency					
B2	**Intercept**	**-0.41**	**0.06**	**-6.57**	<**0.001**
	Magnet	**-5.55**	**1.00**	**-5.54**	<**0.001**
	Procedural Control	**-5.39**	**1.00**	**-5.38**	<**0.001**
Pass Around Frequency					
C2	**Intercept**	**-1.98**	**0.14**	**-14.57**	<**0.001**
	Magnet	**1.67**	**0.15**	**11.21**	<**0.001**
	Procedural Control	**1.79**	**0.15**	**12.03**	<**0.001**

were then placed within the associated categories for each trial and subjected to statistical analyses.

2.3.2. The Barrier Base as an Artificial Reef Structure

When possible, divers conducted basic observational surveys to determine if benthic organisms colonized the base of the Sharksafe barrier. To do this, the entire visible surface of the same nineteen concrete bases (surface area per base ~ 6500 cm^2) were analysed over the course of both years and individual organisms were identified and quantified. Observations were made on a weekly to bi-weekly basis, or when weather permitted.

2.4. Statistical Analysis

Data collected throughout experimentation was in the form of frequencies (i.e. counts) for *C. carcharias.* However, this data was multidimensional, where the main effects of several variables and interaction terms between these variables were of interest. Therefore, the traditional Chi-square analysis was inefficient in testing hypotheses that involve the multi-dimensions, and instead, we applied a Poisson generalized

Table 4
The aggregated behavioral interactions of "unidentified sharks". This table represents the overall behavioral interactions that were recorded when white sharks (*Carcharodon carcharias*) could not be accurately identified.

Region	Total Visits	Total Avoidances	Total Entrances	Total Pass Arounds
Control	39	0	21	6
Procedural Control	33	2	0	19
Magnet	46	8	0	25

linear mixed effect model to data for each behavioral category: avoidance, entrance and pass-around, respectively. The multinomial distribution is the joint distribution of Poisson distributions, conditional upon their total sum (Dobson and Barnett, 2008). Furthermore, treatment positioning was not randomized throughout experimentation, and thus *C. carcharias* behaviors were not considered independent since multiple interactions from one individual may have occurred to identical treatment regions with time. This may violate the assumption in generalized linear models that data are independent and further explains why generalized linear mixed effect models were used. Thus we treated individual shark as a random effect due to data non-independence whereas we treated the other variables as fixed effects.

Mathematical form of our generalized linear mixed effect model is:

$$Y = X\beta + S + \varepsilon \tag{1}$$

where Y represents the response variable, X is the design matrix of explanatory variables, including all possible interaction terms, β is the column vector of coefficients that correspond to explanatory variables, S is the vector of individual sharks, which is a random effect, and ε represents the vector of errors, assumed to follow a normal (Gaussian) distribution whose mean is zero and whose variance is constant. The fixed effects in this study were treatment type (discrete), conspecific density (continuous), water visibility (continuous), and exposure quantity (discrete).

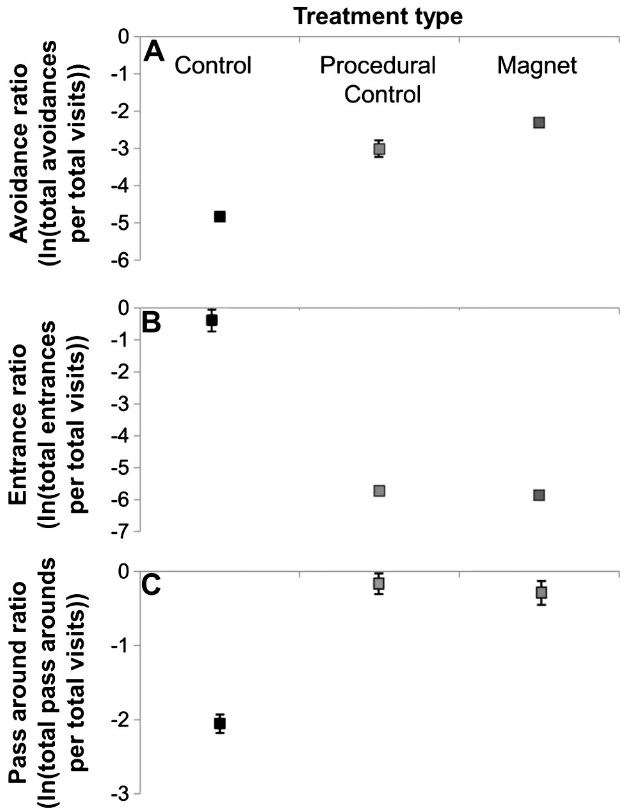

Fig. 3. Graphical representation (ln(total frequency of behavior/total visits)) for the best fit models for each response variable pertaining to the white shark (*Carcharodon carcharias*) during the Sharksafe barrier experiment. Error bars show the standard error. A) Avoidance ratio (A2). B) Entrance ratio (B2). For entrance ratio, all data were transformed to (ln(total entrances + 1/total visits) for each treatment type to improve the interpretability of the data, since no entrances were observed towards both the procedural control and magnet regions during experimentation. C) Pass around ratio (C2).

We implemented the mixed effect model, using the 'lme4' package of R (Bates et al., 2012; Hyun et al., 2014; R 3.3.0 Statistical Program). Forward selection was used to determine the best fit model for the data, starting with a null model of which subsequent models were created by adding one or several explanatory variables to determine their effect on the response variables (i.e. avoidance frequency, entrance frequency, and pass around frequency). Model selection criteria included: Akaike Information Criteria (AIC), and behavior of model residuals using a quantile-quantile (Q-Q) plot, and associated *P*-values. Lastly, no entrances were observed towards the procedural control and magnet regions, whereas a substantial quantity of entrances was observed toward the control region. Therefore to permit model implementation, entrance data were transformed by adding one behavioral count to each treatment region (i.e. one entrance and visit towards the control, procedural control, and magnet regions).

3. Results

A total of forty-nine, one-hour trials were conducted over the course of twenty-four days during the two-year period. Upon initial inspection, year (Y) was found to have no significant influence on response variables. This justified data aggregation over the two year period to increase sample size and the subsequent dropping of this variable from model formulation. For the first study year (June-August 2012), twenty-three different sharks were identified using short-term identification characteristics and post-hoc video analysis. For the second study year (May-August 2013), forty-four different sharks were identified, with four of these being re-sighted individuals from the previous year. Therefore, the overall inter-annual total number of unique sharks was sixty-three. Using the vessel(s) as a reference, it was estimated that sharks ranged from 2 to 5 m in total length. Throughout experimentation, sea surface temperature was 14.8 °C ± 0.66 (mean ± standard deviation), salinity was 43.04 ppt ± 2.56, water visibility was 4.58 m ± 1.47, and conspecific density ranged from 1 to 5.

3.1. Avoidance Frequency

When focusing solely on the avoidance frequency, the main effect of treatment type was significant, whereas all other candidate variables were not significant and thus excluded from the model. For avoidance frequency, model A2 was selected and contained an AIC of 240.62 (Table 2), with the magnetic treatment (2.32, $t = 4.42$, $P < 0.001$; Table 3) and procedural control treatment (1.36, $t = 2.37$, $P = 0.02$; Table 3) yielding a significant increase in avoidance frequency in comparison to the control treatment (Fig. 3a). Furthermore, based on the obtained coefficients, the magnetic treatment yielded a substantially greater avoidance frequency in comparison to the procedural control region.

3.2. Entrance Frequency

Data pertaining to entrance frequency exhibited a clear behavioral distinction between treatment types (Control = 256, Procedural Control and Magnet = 0). However, for secondary validation, an applied Poisson regression to the transformed data (i.e. adding one behavioral count to each treatment type) pertaining to the logarithm of entrance frequency (referred to as "entrance frequency" for the remaining text), revealed that the main effect of treatment type was significant, whereas all other candidate variables were not significant and thus excluded from the model. For the entrance frequency, model B2 was selected and contained an AIC of 281.64 (Table 2) with the magnetic treatment (-5.55, $t = -5.54$, $P < 0.001$; Table 3) and procedural control treatment (-5.39, $t = -5.38$, $P < 0.001$; Table 3) yielding a significant

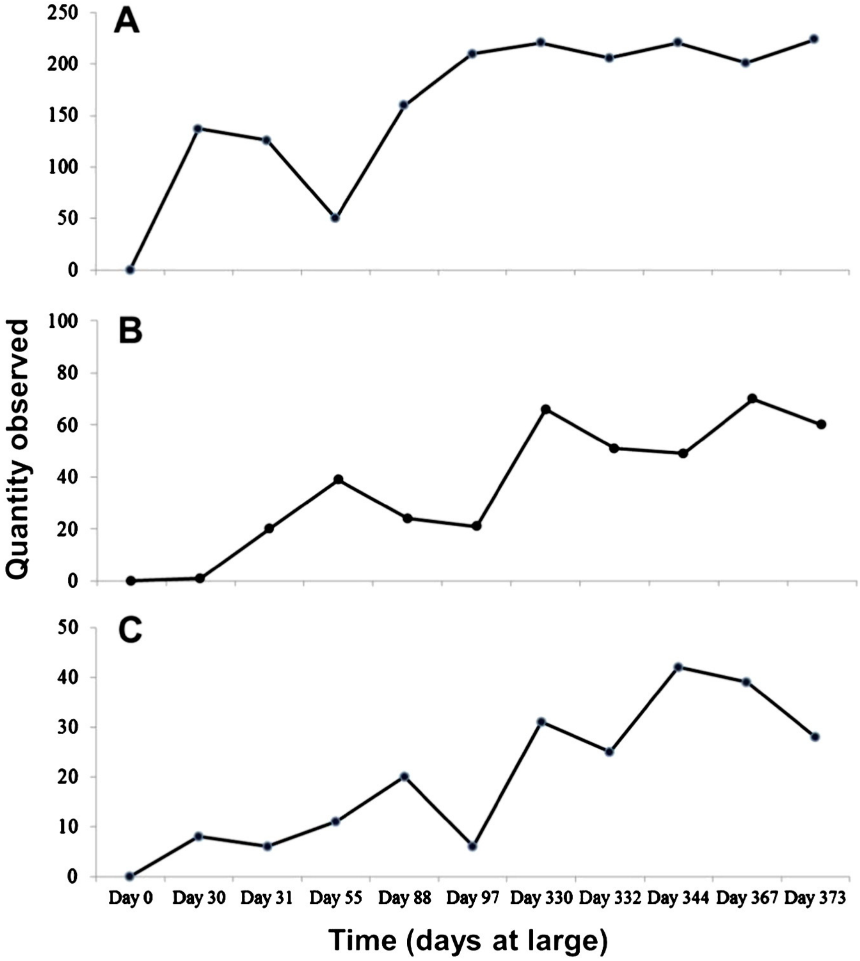

Fig. 4. Benthic organismal colonization on the Sharksafe barrier. These figures represent the survey counts obtained from the same 19 concrete blocks over the course of 373 days of deployment. For each survey, the entire visible surface of each concrete block (surface area per block ~ 6500 cm^2) was analysed and organisms were identified and quantified. A) Cape sea urchin (*Parechinus angulosus*), B) Dwarf cushion stars (*Patiriell exigua*) and C) South African turban snail (*Turbo sarmaticus*).

decrease in entrance frequency in comparison to the control treatment (Fig. 3b). Furthermore, based on the obtained coefficients, these findings illustrate that both the procedural control and magnetic treatments had a similar effect on entrance frequency.

Fig. 5. Cape fur seals (*Arctocephalus pusillus pusillus*) swimming throughout the barrier. This photograph was taken during one maintenance dive where *A. pusillus pusillus* was observed to swim throughout all of the experimental regions. © Michael Rutzen.

3.3. Pass Around Frequency

When focusing solely on the logarithm of pass around frequency (referred to as "pass around frequency" for the remaining text), the main effect of treatment type was significant, whereas all other candidate variables were not significant and thus excluded from the model. For the pass around frequency, model C2 was selected and contained the lowest AIC of 645.15 (Table 2) with the magnetic treatment (1.67, $t = 11.21$, $P < 0.001$; Table 3) and procedural control treatment (1.79, $t = 12.03$, $P < 0.001$; Table 3) yielding a significant increase in pass around frequency in comparison to the control treatment (Fig. 3c). Furthermore, based on the obtained coefficients, these findings illustrate that both the procedural control and magnetic treatments had a similar effect on pass around frequency.

3.4. Observation of the Barrier as an Artificial Reef Structure

Throughout experimentation, a total of eleven intermittent surveys were conducted from day 0 of base deployment until day 373. Species exhibiting the highest abundances were the Cape sea urchin (*Parechinus angulosus*; Fig. 4a), dwarf cushion star (*Patiriella exigua*; Fig. 4b), South African turban snail (*Turbo sarmaticus*; Fig. 4c), and the black sea cucumber (*Pseudocnella sykion*). Rapid colonization of these species was observed until day 330, after which organismal density remained relatively unchanged.

3.5. Cape Fur Seal Observations

Throughout the year when *C. carcharias* behavioral analyses were not being conducted, the structural integrity of the barrier was assessed through passive observations (i.e. topside observations from a vessel). It was only during this time and on one occasion that *A. pusillus pusillus* were observed around the barrier. Approximately twenty *A. pusillus pusillus* were observed swimming throughout all regions of barrier and there were no indications of attraction, irritation or avoidance (Fig. 5).

4. Discussion

This study aimed to determine if the Sharksafe barrier, a barrier containing both visual and magnetic stimuli, could effectively manipulate the swim patterns of *C. carcharias*. During experimentation, the swimming behavior of all interacting sharks (n = 63) was manipulated in response to both the procedural control and magnetic regions of the barrier, which was evidenced by an increase in avoidance and pass around frequencies and a decrease in entrance frequencies in comparison to the control region. In fact, no *C. carcharias* swam through the magnetic and procedural control regions of the barrier, while sharks made 256 entrances through the control regions. In addition, explanatory variables such as experiment year, water visibility, conspecific density, and exposure quantity did not statistically affect *C. carcharias* behavior in relation to all barrier regions.

4.1. Basic Behavioral Observations

This experiment illustrated how the procedural control and magnetic regions of the barrier impacted *C. carcharias* swim patterns. More specifically, avoidance frequency was highest towards the magnetic region. However, avoidance behaviors were infrequent and may be a result of sharks responding gradually and at greater distances due to the visual stimuli associated with the barrier. For example, sharks were observed to swim within visual range (i.e. several meters corresponding with water visibility properties) of the barrier, which often exceeded the maximum magnetic flux distance (i.e. ~30-50 cm; O'Connell et al., 2011) associated with the magnetic region. Of the occasions where the sharks swam within close range of the magnets, strong avoidance behaviors were observed and for such situations, it is suggested that magnets may be important for barrier efficacy.

Entrance frequency was highest towards the control region, with no entrances through the procedural control and magnetic regions. Similar to a previously conducted study (O'Connell et al., 2012), both visual and magnetic stimuli were effective at manipulating the swimming patterns of interacting *C. carcharias* and therefore support the present findings. However, unlike the present study, in O'Connell et al. (2012), entrance behaviors did occur through both the procedural control (20% of visits to this region resulted in an entrance) and magnetic (4% of visits to this region resulted in an entrance) regions. In O'Connell et al. (2012), inter-column spacing was 2 m whereas in the present study, the three alternating rows minimized inter-barrier element spacing to 1 m. It is therefore possible that this structural modification provided substantial visual enhancement and maximized barrier efficacy.

Pass around frequency was highest towards the procedural control and magnetic regions. These findings may be explained by the high visual acuity and vision-reliance of *C. carcharias* (Gruber and Cohen, 1985; Strong, 1996). Having a high reliance on vision may inadvertently result in the ability for visual stimuli to drastically alter *C. carcharias* behavior and therefore would explain behavioral differences between the control versus the remaining experimental regions (i.e. procedural control and magnetic).

Based on these findings, it is evident that both the procedural control and magnetic regions of the barrier are sufficient to elicit behavioral modification. This similarity in effectiveness raises curiosity for the justification for magnetic inclusion. However, similar research on bull (*Carcharhinus leucas*) and great hammerhead (*Sphyrna mokarran*) sharks illustrates that magnetic barriers, in comparison to procedural control barriers, maximize swim pattern manipulation (O'Connell et al., 2013b). Although not directly measured, inter-specific variations in shark behavior may be directly linked to the behavioral ecology of each species. For example, *C. carcharias* is highly reliant on vision for prey capture (Strong, 1996) and therefore would explain why the visual stimuli associated with the procedural control region was sufficient to elicit similar behavioral patterns as was observed towards the magnetic region. In contrast, *C. leucas* is often associated with high turbidity freshwater, estuarine and coastal environments (Curtis et al., 2013; Heupel and Simpfendorfer, 2008), and thus may be more reliant on their electrosensory system than their visual system during navigating and foraging. Furthermore, hammerheads have a maximum pore density occurring on the ventral surface of their cephalofoils (Kajiura, 2001; Kajiura et al., 2003), and also as a consequence of their head shape, hammerheads have a characteristically greater lateral search area (Kajiura and Holland, 2002). These *C. leucas* and *S. mokarran* characteristics may make these animals more sensitive and susceptible to magnetic repellents, illustrating not only why inter-specific variation may occur but also why magnets may be important for future inclusion in repellent technologies.

4.2. The Influence of Explanatory Variables on Shark Behavior

4.2.1. Water Visibility

Previous studies demonstrate how variations in water visibility parameters can alter fish behavior (Leahy et al., 2011; Ranåker et al., 2012; O'Connell et al., 2013a). These behavioral changes are referred to as context-dependant switching, where a short-term deprivation in one sensory system can lead to a heightened reliance on another (Leahy et al., 2011; Ranåker et al., 2012). For example, in comparison to sighted sharks, visually deprived lemon sharks (*Negaprion brevirostris*) exhibited behavioral changes (i.e. increased avoidance and decreased entrance frequency) towards permanent magnetic regions of an experimental pen (O'Connell et al., 2013a). These findings suggest that the addition of permanent magnets may maximize Sharksafe barrier effectiveness, especially in situations where water visibility characteristics (e.g. increased turbidity) are substantially limited. However, since all observations in the present study were conducted during daylight hours and in water visibility conditions that were greater than or equal to 3 m, the visual range may not have been sufficient to elicit these behavioral changes as observed in the previous study (O'Connell et al., 2013a), thus the true utility of magnets for *C. carcharias* swim pattern manipulation towards the Sharksafe barrier is uncertain.

4.2.2. Conspecific Density

Sharks are characterized by utilizing mechanisms such as rheotaxis – orienting into oncoming current (Hodgson and Mathewson, 1971; Peach, 2002) and/or klinotaxis – directional orientation governed by stimulus gradients (Mathewson and Hodgson, 1972) to aid in locating food sources. In the present study, even though the visual stimulus associated with bait was lacking, it was originally hypothesized that the olfactory cues associated with the natural fish chum would induce chemical-induced rheotaxis and/or klinotaxis yielding a competitive mentality among interacting sharks. Similar to previous electrosensory repellent studies conducted on spiny dogfish (*Squalus acanthias*; Tallack and Mandelman, 2009) and Galapagos sharks (*Carcharhinus galapagensis*; Robbins et al., 2011), this competitive mentality was hypothesized to reduce the effectiveness of the barrier, thus resulting in a decrease in avoidance frequency towards the magnetic region and an increased entrance frequency through all regions of the barrier. However, the present study illustrates that variations in *C. carcharias* density did not influence magnetic repellent efficacy and may be explained by: (1) the density-induced behavioral responses to electrosensory stimuli being species-specific, (2) barrier design being so effective that even though a competitive mentality may have been induced, repellency or swim pattern manipulation was not compromised, and (3) the overall length of each section of the barrier was minimal and therefore sharks could simply navigate around the barrier to search for the food source and thus competitively-induced behaviors were not observed. Therefore, future baited experiments may be conducted to assess the barrier's ability to exclude motivated sharks of varying density levels which would provide insight into the barrier's overall utility.

4.2.3. Habituation

Elasmobranch-related studies demonstrate that repeated exposure to an unchanging auditory stimulus could lead to rapid habituation; however, variations in pulse and/or frequency can prolong this habituation (Myrberg et al., 1969, 1978). Similar to this concept, *C. carcharias* habituation may not have been observed towards the magnetic region since magnets were not permanently affixed, but rather constantly changing orientation with variations in current and wave forces. This movement, similar to pulse or frequency variation in Myrberg et al. (1969, 1978), may have exposed interacting sharks to varying magnetic field strengths, thus prolonging and/or alleviating short-term habituation. However, these findings would not explain why sharks did not habituate to the procedural control region. As observed in one previous study, if ants are subjected to a barrier but are presented with sufficient motivation (e.g. food stimulus), they will simply navigate around the barrier for the food reward (Bisch-Knaden and Wehner, 2001). Similar to ants and in the present study, the *C. carcharias* were lured towards a barrier using olfactory cues associated with chum (e.g. food stimulus). Since sharks could simply navigate around the barrier to get to the chum source, this may explain why indications of habituation (e.g. swimming through the barrier) towards the procedural control region were not observed. If true, the present experiment did exhibit the *C. carcharias*-specific behavioral modification capabilities of the Sharksafe barrier. However, barrier length would reveal one limitation of the current experiment and thus future studies employing larger or even exclusion zones constructed out of the Sharksafe barrier are warranted.

4.3. Cape Fur Seal Barrier Interaction

Preliminary and non-quantifiable observations reveal that *A. pusillus pusillus* exhibited no signs of attraction, irritation or avoidance when swimming amongst the barrier elements. Although this single day of observations does not lend conclusive interpretation of the barrier's effect on *A. pusillus pusillus*, the findings illustrate promise for the elasmobranch-specific (or in the context of this study, *C. carcharias*-specific) nature of the Sharksafe barrier. In contrast to shark nets which are non-selective, the Sharksafe barrier may therefore provide one additional conservation benefit, besides potential shark exclusion, that warrants further scientific investigation. More specifically, future analysis may focus heavily on obtaining quantifiable data on other marine mammal species, such as certain cetaceans (e.g. common dolphin – *Delphinus delphis*, bottlenose dolphin - *Tursiops truncatus* and the humpback dolphin – *Sousa plumbea*), since there exists a large ecological overlap between these species and shark nets.

4.4. Biofouling

It was of concern that biofouling may limit the barrier's buoyancy, which may impact the vertical profile and ability of the barrier to manipulate shark behavior. In the present study, the longest barrier element deployment duration was seven months. Of the piping that remained in the water throughout this duration, thin green algae colonized the pipe surface making barrier element color and texture more closely resemble *E. maxima*. After examining the internal portion of the pipes, extensive barnacle growth was observed; however, growth was limited by space availability as barnacles could not grow in the space occupied by high density foam. Therefore, the future utilization of high density foam to fully replace these regions currently occupied by barnacles will not only maximize buoyancy, barrier longevity, and help maintain the vertical profile of the barrier, but may also limit biofouling.

5. Conclusions

The successful implementation and demonstration of the Sharksafe barrier on manipulating *C. carcharias* behavior provides a foundation for future conservation engineering research. Furthermore, the long-term deployment illustrated the barrier's ability to withstand harsh environmental conditions and how the barrier's foundation promotes benthic organismal colonization. Therefore, with the continued decline of several shark populations and the present findings illustrating that the Sharksafe barrier can manipulate *C. carcharias* swim patterns, it is imperative that future studies examine the barrier's shark exclusion properties. With sharks swimming through the eight meter control region that existed between the magnetic and procedural control regions, it is evident that exclusion trials would require a full barrier without gaps to maximize potential success. These findings will determine if the barrier can be deployed to create exclusion zones which may serve as bather protection systems, shark conservation tools, and a potential eco-friendly alternative to the presently used bather protection strategies, such as shark nets, drumlins and/or shark culls.

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