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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.,