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Effects of the Shark Shield™ electric deterrent on the behaviour of white sharks (*Carcharodon carcharias*)


C. Huveneers[1,2], P.J. Rogers[1], J. Semmens[3], C. Beckmann[2], A.A. Kock[4,5], B. Page[1] & S.D. Goldsworthy[1]

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Final Report to SafeWork South Australia

Government of South Australia

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EXECUTIVE SUMMARY

- Although shark attacks are rare, their impacts on humans can have serious consequences. Attacks have increased in Australia from 6.5 to 15 incidents per year in the last decade.
- One of the most popular personal protective devices used to reduce the risk of shark attack is the Shark Shield^{TM} electric deterrent, although its effectiveness has never been subject to independent scientific testing.
- The present study tested the effects of the Shark Shield Freedom7^{TM} electric deterrent on (1) the behaviour of white sharks (*Carcharodon carcharias*) around a static bait, and (2) the rates of attacks on a towed seal decoy.
- A total of 116 trials using a static bait were undertaken at the Neptune Islands, South Australia and 189 tows were conducted using a seal decoy near Seal Island, South Africa.
- The proportion of baits taken during static bait trials was not affected by the deterrent. The deterrent increased the time it took to take a static bait, and the number of interactions per approach. The effect of the Shark Shield^{TM} was not uniform across all sharks.
- The number of interactions within two metres of the deterrent decreased when it was activated.
- No breaches and only two surface interactions were observed during the dynamic seal decoy tows when the deterrent was activated, compared to 16 breaches and 27 surface interactions when the deterrent was not activated.
- Although the fine-scale positioning and presence/absence data collected to assess the potential of the device to attract white sharks was limited to one trip, our results did not suggest that sharks were attracted to the deterrent.
- The results showed that the deterrent had an effect on the behaviour of white sharks, but did not deter or repel them in all situations.
- Future studies should focus on testing the effect of deterrents less than two metres from the bait, in locations not frequented by cage-diving operators, and on other potentially dangerous sharks, such as tiger sharks (*Galeocerdo cuvier*) and bull sharks (*Carcharhinus leucas*).

1. PREFACE

The potential for injuries or death in workplaces and during recreational activities as a result of human-wildlife interactions poses significant concerns for employers and the general public. Human-wildlife interactions that negatively impact human safety occur with large terrestrial vertebrates, e.g. wolves (Linnell et al., 2002), tigers (Goodrich, 2010), and crocodiles (Aust et al., 2009). Occupational Health Safety and Welfare (OHS&W) legislation requires all employers to provide a safe workplace for their staff, including during fieldwork and diving (e.g. *Occupational Health, Safety and Welfare Act 1986* SA). Several private and government organisations, especially in South Australia, use the Shark Shield^{TM} to reduce the risk of shark attack, and provide a safer environment as part of their standard operating procedures and OHS&W duty of care. Despite this, several shark attacks involving people undertaking workplace activities have occurred. This includes attacks on a wildlife tourism operator (Western Australia, October 2010), a scallop diver (South Australia, April 2002), a scientific diver (South Australia, August 2005), and an abalone diver in February 2011 (Australian Shark Attack File, unpublished data). During these events, coronial inquests revealed that an electric deterrent was not worn in one instance, that the device was either turned off or not used appropriately in two instances, and that the operational status of the electric deterrent in the last event is still subject to coronial investigations.

With the recent increasing occurrence of shark attacks, and the emphasis on workplace safety, there is a need for risk reduction benefits of shark deterrent to be independently and scientifically tested. As a result, SafeWork SA commissioned a study to improve our understanding of the effects of the Shark Shield^{TM} on the behaviour of white shark (*Carcharodon carcharias*). The study aimed to provide relevant data to assist decision-making in the role of the Shark Shield^{TM} in the Australian/New Zealand Standard^{TM} AS/NZ 2299 for occupational diving operations.

2. INTRODUCTION

Although shark attacks are rare, their impacts on humans can have serious consequences. In general, the risk of shark attack is low when compared to other dangers potentially encountered by beachgoers, such as drowning, rip currents, and surfboard accidents (Klimley and Curtis, 2006; Burgess et al., 2010). For example, in Australia there were about 81 fatalities a year from drowning between 2005 and 2010 (Anonymous, 2011), compared to about one fatality per year from shark attack (International Shark Attack File, unpublished data).

Globally, the number of shark attacks has been increasing (Burgess et al., 2010; Curtis et al., 2012). In Australia, the number and risk of shark attacks have also increased, with the number of recorded incidents more than doubling from about 7 per year in 1990–2000 to 15 per year in 2000–2010 (West, 2011). This has coincided with an increasing human population (Burgess et al., 2010), more people visiting beaches, a rising popularity of the coastal lifestyle and marine activities, and increased accessibility of previously isolated coastal areas (West, 2011). While the risk of a fatality from a shark attack in Australia is low, South Australia (SA) has had about 70% more fatalities per capita in 1990–2010 than any other State or Territory (Australian Shark Attack File, unpublished data). The distribution and number of fatalities is likely related to the distribution and abundance of the potentially dangerous shark species along the Australian coastline (Curtis et al., 2012). One of the greatest concentrations of white sharks, which are responsible for most of the fatal attacks (West, 2011; Curtis et al., 2012), is considered to occur in South Australia (Last and Stevens, 2009).

Substantial efforts have been made by government agencies to reduce the probability of shark attacks on the general public. A series of fatal attacks in 2006 led to various meetings and workshops around the world to describe and review the various shark attack mitigation measures and shark safety programs worldwide, and assess the best means to mitigate and respond to such shark attacks (Anonymous, 2006a; Anonymous, 2006b; Nel and Peschak, 2006). The increased recognition of shark vulnerability to population decline (Simpfendorfer et al., 2011), and interest in shark attacks and means to reduce their likelihood has also led to a recent publication reviewing shark attack patterns (West, 2011) and recommendations to government agencies responsible for responding to incidents of shark attacks (Curtis et al., 2012).

Prevention efforts and responses to shark attacks have varied temporally and regionally, and have included shark hunts, organised shark culling programs, beach meshing and drumlines, beach closures, shark fences, land- and aerial-based shark spotting, and acoustic telemetry (for a review, see Curtis et al. (2012)). While these measures aim to reduce the probability of a shark-human encounter, other measures aim to directly repel sharks from approaching individuals undertaking marine activities. These deterrents have been developed to illicit a response by impacting on one or more of the shark senses, including vision, smell, taste, and electro-reception (Table 1). For example, various aposematic colour configurations (use of colours as anti-predator tactics) have been proposed to allegedly repel sharks. The use of chemicals as shark repellents has also been proposed (Baldridge, 1990; Rasmussen and Schmidt, 1992; Sisneros and Nelson, 2001). The sensitivity of the electro-receptive organ of sharks, however, has been the most studied in relation to developing a shark repellent.

Sharks and rays are capable of detecting weak electromagnetic fields (Kalmijn, 1966). Several biological functions of the ampullary electrosense have been proposed, including prey detection (Kalmijn, 1971; Blonder and Alevizon, 1988; Lowe et al., 1994; Haine et al., 2001; Kajiura and Holland, 2002a), detection of predators (Peters and Evers, 1985; Sisneros et al., 1998), social communication (Bratton and Ayers, 1987; Sisneros et al., 1998), detection of mates (Tricas et al., 1995) and magnetoreception/geonavigation (Kalmijn, 1974; Kalmijn, 1978; Paulin, 1995). The electro-reception detection threshold is species-specific, but sharks and rays are able to respond physiologically and behaviourally to weak, low frequency electric fields of 10 nV/cm and 5 nV/cm, respectively (Dijkgraff and Kalmijn, 1962; Dijkgraaf and Kalmijn, 1966; Kalmijn, 1982), and show a behavioural response at levels as low as <1nV/cm (Kajiura and Holland, 2002b; Jordan et al., 2011). Ongoing studies initiated in the 1960s have attempted to overwhelm the electro-receptive organs to deter sharks by applying a strong localised electric or magnetic field, (Smith, 1966; Gilbert and Gilbert, 1973; Smith, 1973; Smith, 1974; Smith, 1990). It has also been speculated that sharks might detect the pulses emitted by an electric deterrent from a long distance and confuse it with that emitted by potential prey. This has created growing concerns that electric deterrents may attract sharks from a distance prior to repelling them when in close proximity.

Table 1. Examples of shark deterrent available.

Sensory organ	Product	Webpage
Vision-based deterrent	The 'Shark Camo'	surfershotshop.com/vmchk/surf-accessories/surf-essentials/shark-camo-shark-repellent.html
	Extreme green laser	www.airbuddy.com/id47.htm
	Sharkproof mask strap	www.sharks-diving.com
Taste-based deterrent	Bite kit	www.repelsharks.com/index.php?main_page=product_info&cPath=9&products_id=12
Smell-based deterrent	Aerosol canisters	www.repelsharks.com/index.php?main_page=index&cPath=1
	BCB Shark repellent	www.bestglide.com/shark_repellent.html
Electro-reception-based deterrent	Shark Shocker	thesharkshocker.com
	AquaShield	www.aquashield.us.com
	Magnetic string anklet	www.repelsharks.com/index.php?main_page=index&cPath=7&zenid=l43jeuqgptbhdbf08juusie4o6
	Electronic Shark Defence System	www.surfertoday.com/surfing/7071-electronic-shark-defense-system-is-activated
	Shark Shield™	sharkshield.com

The scientific robustness of the tests undertaken to assess the efficacy of these various devices varies extensively. Only a few shark repellents have been scientifically tested with results published in peer-reviewed literature: rare earth metals (Kaimmer and Stoner, 2008; Stoner and Kaimmer, 2008; Wang et al., 2008; Brill et al., 2009; Tallack and Mandelman, 2009; Robbins et al., 2011) and magnets have been tested for use as shark bycatch and depredation mitigation (Rigg et al., 2009; Robbins et al., 2011), whereas semiochemical repellents (Sisneros and Nelson, 2001) and electric impulses (Smit and Peddemors, 2003; Robbins and Peddemors, unpublished data; Broad et al., 2010) have been tested as personal shark deterrent.

Electric shark deterrents have become the most popular personal protective devices. Research on electric deterrents was first initiated in the 1960s by the South African Council for Scientific and Industrial Research (Smith, 1973; Smith, 1974; Smith, 1990) for beach protection. This program was discontinued in 1988 due to the maintenance costs of such a system and following an ineffective trial (Cliff, 1988). The inefficacy of the electric barrier was later attributed to inadequate handling and lack of recovery of the shark test subjects, rather than the actual failure of the system (Smith, 1990). The Natal Sharks Board (NSB), (now called KwaZulu Natal Sharks Board, KZNSB), subsequently investigated the concept of using electrical fields to create a personal deterrent. As a result, the SharkPOD™ (Protective Oceanic Device) was invented and patented in 1995. The KZNSB led various tests of the SharkPOD™, which concluded that the probability of an attack was reduced from about 0.70 in power-off mode to about 0.08 in power-on mode (Smit and Peddemors, 2003). In 1999, an

Australian company, SeaChange (now Shark Shield Pty Ltd), was established to develop and produce a modern range of electric shark deterrents based on the SharkPOD^{TM} patented waveform technology. Several personal protection devices were created under the label of Shark Shield^{TM}.

While the electric waveform was not changed between the SharkPOD™ and SharkShield Freedom7™, the configuration of the electrodes was, as well as the casing of the electronic components and the way the device is worn. In the case of a SharkPOD^{TM}, one electrode was worn on the scuba diver's tank with the other electrode located on the ankle of the diver, which is the equivalent to the Shark Shield Scuba7^{TM}, whereas with a Shark Shield Freedom7^{TM}, divers have both electrodes streaming off an ankle strap with the first electrode about 10–20 cm off the ankle and the second electrode about 200 cm from the diver. Due to this change, SeaChange undertook in-house testing of the strength of the Shark Shield^{TM} electric pulse (P. Gapp, pers. comm.). The effects of the currently available Shark Shield^{TM}, however, have never been independently and scientifically tested.

2.1 Objectives

The objective of this study was to assess the effects of the Shark Shield Freedom7^{TM} on the behaviour of white sharks. This species was selected because it is responsible for the most unprovoked attacks and fatalities (in Australia, 19.5% and 34%, respectively) (West, 2011; Curtis et al., 2012). Specifically, we aimed to:

1. Assess the efficacy of the Shark Shield Freedom7^{TM} at reducing or preventing white sharks from obtaining (1) a natural prey item, and (2) a towed seal decoy;
2. Investigate the behavioural response of white sharks exposed to a Shark Shield Freedom7^{TM}; and
3. Determine if the Shark Shield Freedom7^{TM} attracts white sharks from a distance prior to repelling them at closer range.

3. METHODS

Field experiments were designed to test the effects of the Shark Shield Freedom7^{TM} electric deterrent (hereafter referred to as the deterrent) on (1) the behaviour of white sharks around a static bait, and (2) rates of attacks on a towed seal decoy.

3.1 Static bait experiments

3.1.1 Study site

The static bait experiments were undertaken at the North Neptune Island group (35°149 S; 136°049 E) about 25 km south of Spencer Gulf, on three occasions: Trip 1: 11/10/2010–14/10/2010, Trip 2: 8/02/2011–10/02/2011, and Trip 3: 6/07/2011–7/07/2011 (Figure 1).

The Neptune Islands have been the site of commercial cage-diving with white sharks since the late 1970s (Bruce 2009). While other areas were previously also used for cage-diving, in 2002 all commercial operations were restricted to the Neptune Islands Conservation Park. Both the South and North Neptune groups are open to cage-diving operations, but the North Neptune group is most frequently used (Bruce and Bradford, 2011).

3.1.2 Experiments

White sharks were attracted to the vessel using an odour corridor consisting of unrefined fish oil, minced southern bluefin tuna *Thunnus maccoyii* (SBT) and its blood, and sea water, delivered at a low rate through overflowing the container with a continuous flow of water. Sections of SBT were attached with short lengths of natural fibre to a float and to a line of about 15 m in length. The SBT section was allowed to drift from the stern of the vessel to attract white sharks.

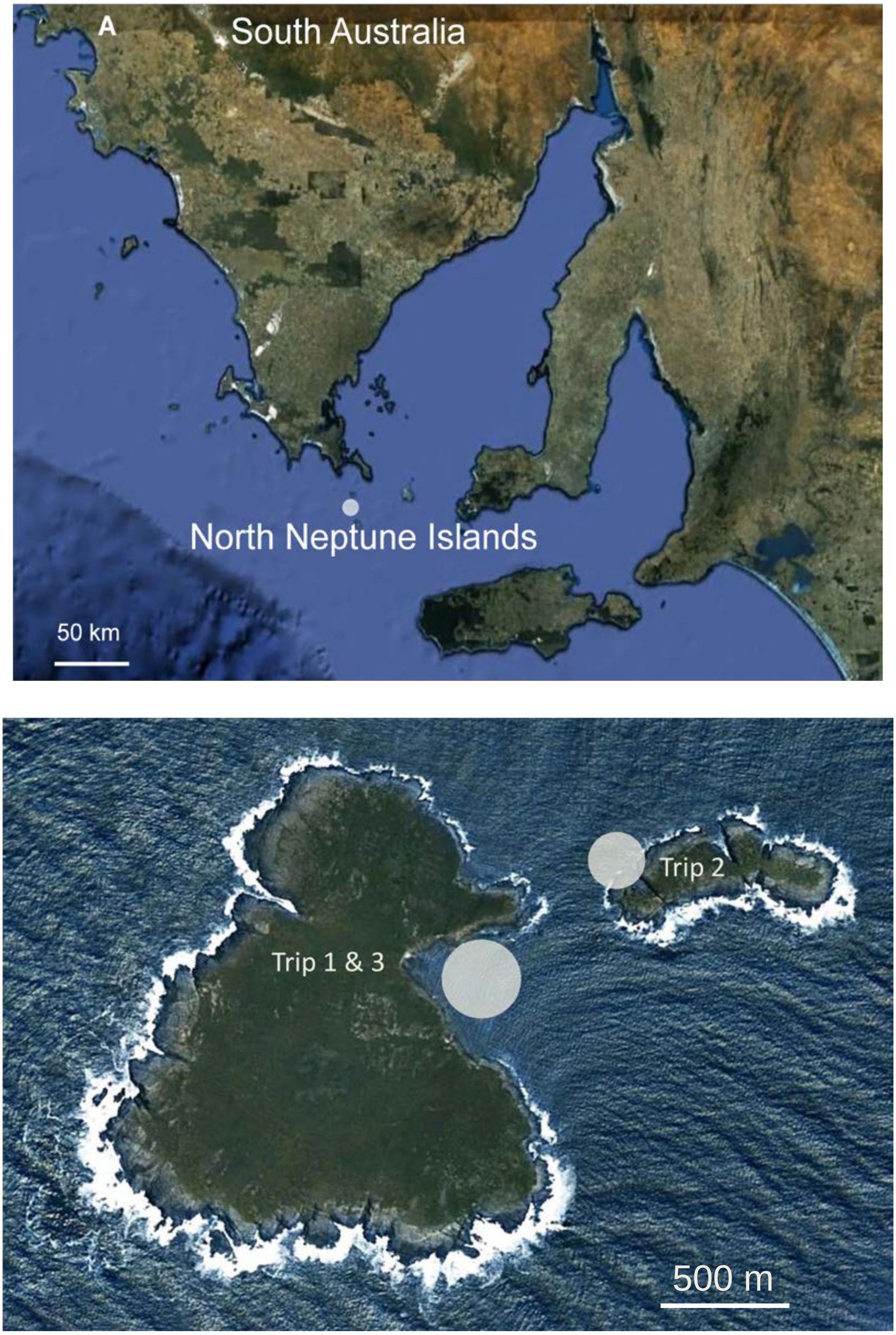

Figure 1. Location of (A) the North Neptune Island group and (B) where static bait experiments were undertaken.

Trials commenced after a white shark was sighted near the vessel at least twice within five minutes or when a shark showed consistent interest in the tethered bait. Each trial consisted of the deployment of fresh SBT bait (about 6 kg). The head and tail section of the SBT tuna were not used during the trials to keep the size and weight of the bait consistent. The bait was attached about 50 cm beneath a small foam float (150 mm diameter), which was kept 150 cm from a large foam float (305 mm diameter) by a PVC pipe (Figure 2). A 2-mm diameter plastic-coated wire 550 mm in length was attached to the large foam float, with two about 2 kg dive weights attached to its distal end. A deterrent was attached to the wire 150 cm below the large foam float and a waterproof camera (GoPro™) was attached at the end of the wire, 400 cm away from the deterrent (550 cm from the large float). The large foam float was connected to the stern of the anchored vessel and left to drift with the wind and tide at a distance of 5–15 m from the vessel. The distance of the equipment from the vessel varied depending on the wind, swell, tide, and glare conditions to ensure that surface observers could record the behaviour of the sharks accurately. Another small foam float (150 mm diameter) was attached 3 m from the large foam float on the line between the vessel and the large foam float to provide a known measurement and help with the estimation of shark total length and distance between a shark and the equipment (Figure 2). The bait and small foam float were kept away from the deterrent and camera to prevent sharks from biting it or becoming entangled in the rope or wire. It also provided a known distance to calibrate shark length and distance. The minimum distance between the bait and the deterrent was 100 cm with the maximum distance being about 300 cm. The static bait was mostly 160–180 cm from the deterrent due to wind and current acting on the deterrent and bait in a similar direction and at the same intensity. The equipment was deployed to replicate the normal use of the deterrent on the ankle of a swimmer or diver with the centre of the electrodes about 180 cm from the head of the user.

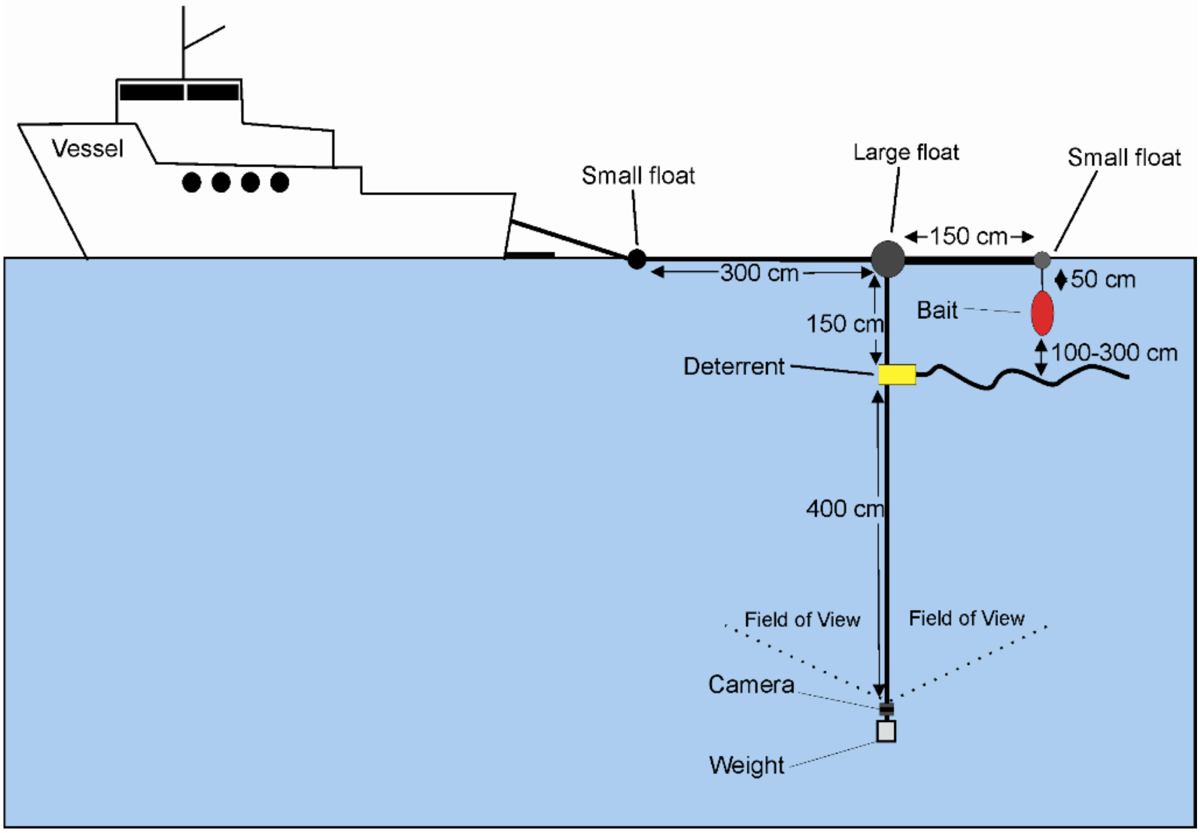

Figure 2. Schematic representation of the experimental set-up used to test the deterrent during static bait trials at North Neptune Island in South Australia.

Each trial was observed by two people and lasted 15 minutes or until a shark took the bait. The status of the deterrent (on or off) was randomised before each trial. Prior to and following each trial during which the deterrent was switched on, the device was tested to ensure that electric impulses were being emitted and that the individual trial was undertaken with the deterrent operating according to the manufacturer's specifications.

The following terminology was used to describe shark behaviour and assess the effects of the deterrent.

Approach (Figure 3) – An *approach* was defined as when a shark was observed within 20 m of the static bait and deterrent. In most situations, observers were not able to maintain visual contact with a shark when it was > 20 m from the static bait and deterrent.

Interaction (Figure 3) – An *interaction* was defined as a directed swim towards the static bait. Each time a shark veered away from the static bait and went back towards the static bait, it was considered as a new *interaction*. The first interaction coincided with an *approach* until the shark turned away from the static bait. A shark then either swam > 20 m away from the static bait (one *approach*, one *interaction*), or turned around and took another directed swim towards the static bait (one *approach*, two *interactions*). An *approach* always had at least one *interaction*, but could have several interactions within an *approach* sequence. Supplementary electronic information A provides an example of a white shark taking the bait preceded by one approach and one interaction. Supplementary electronic information B provides an example of a white shark making one approach with six interactions before taking the bait.

During each trial, the number of individual approaches was recorded. For each approach, the number of interactions was recorded. For each interaction, the minimum distance between the shark and the deterrent was recorded (hereafter referred to as distance) as well as whether a shark took the static bait. The start time of the trial, the time of the first approach (indicating how long it took for a shark to show initial interest in the bait), and the length of the trial (15 minutes or less if a shark took the static bait) were also recorded.

Shark identity was recorded for each individual shark using natural markings and colouration (Domeier and Nasby-Lucas, 2007). Three physical features were used for shark identification: the trailing edge of the first dorsal fin (e.g., Anderson et al., 2011; Chapple et al., 2011), the pigmentation of the lower caudal fin (e.g., Domeier and Nasby-Lucas, 2007), and external markings or scars (e.g., fin damage, major scars).

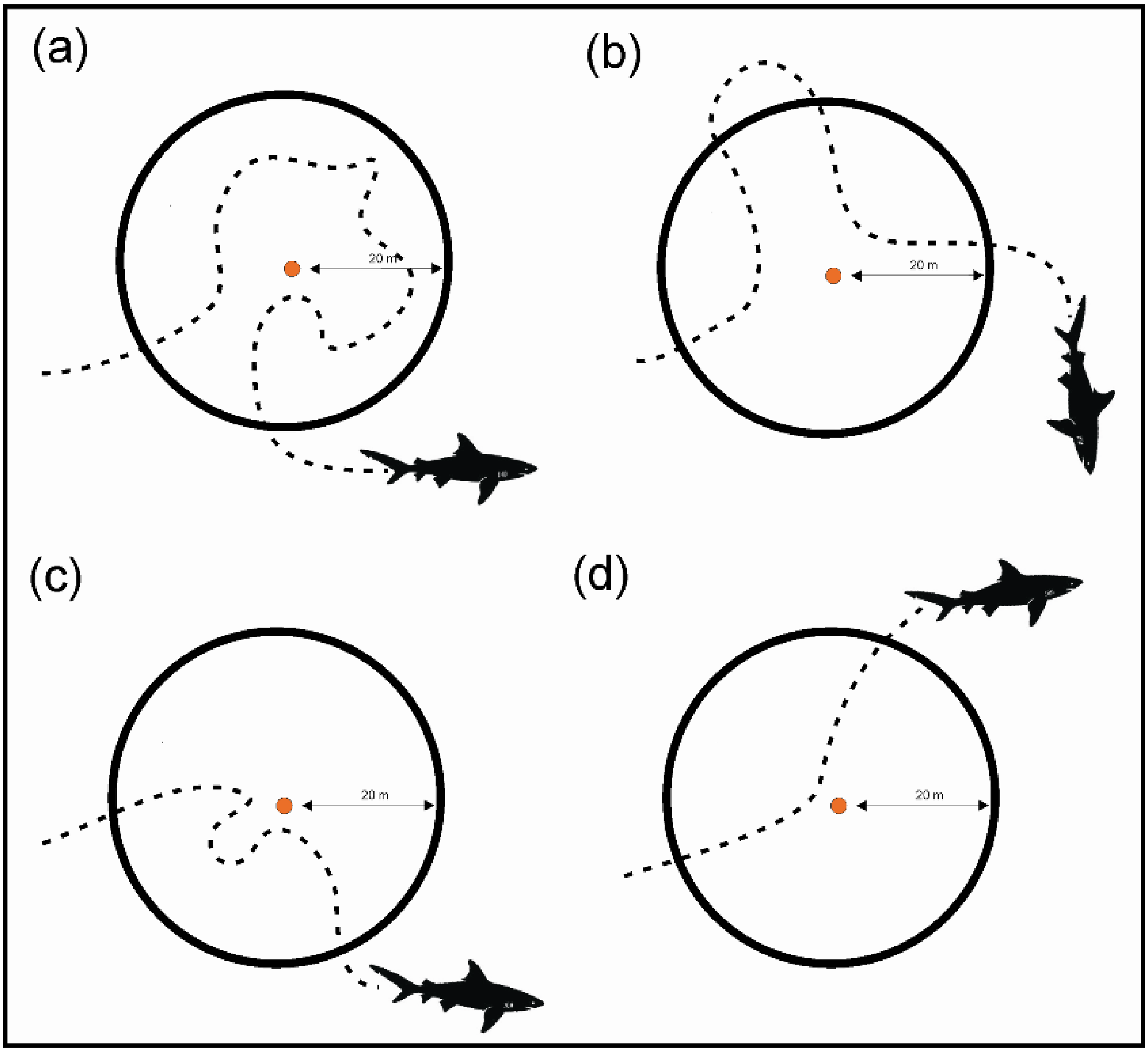

Figure 3. Schematic representation of shark approaches and interactions. The bold circle represents the range up to which observers were capable of reliably sighting sharks (20 m); the orange circle represents the position of the static bait; the dashed line represents the track of the shark. (a) shows one approach with three interactions; (b) shows two approaches with one interaction each; (c) represent one approach with two interactions; (d) represent one approach with one interaction.

Several response variables were used to assess the effects of the deterrent:

(1) The proportion of static baits taken by sharks was recorded to test whether an activated deterrent was effective at reducing or preventing baits being eaten;
(2) The time for the first approach (hereafter referred to as '*approach time*'), defined as the time between deployment of the experimental gear and the first approach within 20 m from the bait, was recorded to determine if sharks already present in the area were attracted to an activated deterrent prior to being repelled from a closer distance;
(3) The time taken for a shark to take the bait (hereafter referred to as '*bait time*'), defined as the time between deployment of the experimental gear and when sharks

consumed or bit the bait, was recorded to test if sharks took longer to take the bait when the deterrent was activated;

(4) The number of approaches per trial and the number of interactions per approach were recorded to investigate the behaviour of sharks around the bait and test if the number of approaches and interactions were impacted by an activated deterrent; and

(5) For each interaction, the minimum distance between the shark and the deterrent (*distance*) was estimated to assess the distance at which an activated deterrent elicited a behavioural response.

3.1.3 Coding of the approaches and interactions with the deterrent

Digitally recorded video footage from each trial obtained from the underwater camera was reviewed, and independently and blindly coded. 'Coding' refers to recording the number of approaches and interactions and estimating the minimum distance between the shark and the deterrent for each interaction. The coder did not participate in any of the trials and had no prior knowledge of whether the deterrent was turned on or off during each trial. The coder was trained by CH. Five trials were coded by the coder and CH, with the number of approaches and interactions, and distance estimates compared between them. Twenty-three interactions were recorded by the coder and CH. Seventy-four percent of the distance estimates were within 0.5 m accordance between coder and CH. Following the coding, any distance estimates with differences of >0.5 m between the coder and CH were reviewed by both until agreement was reached.

3.1.4 Data analysis

There were two potential analytical biases inherent in the type of data collected: temporal correlation (lack of temporal independence) due to potential habituation of sharks or their change in motivation through time, and pseudo-replication due to the same shark interacting with the bait within and across trials. For example, sharks may have become habituated to the presence of an activated deterrent and the electric pulses emitted. Similarly, sharks, which took on the bait, may have become less likely to be impacted by an activated deterrent due to positive reinforcement provided by the bait.

Temporal correlation was tested by estimating the Pearson product-moment correlation coefficient (PPMCC) for each response variable across time. The replicates varied across response variables (e.g., a distance was estimated for each interaction, but one approach time was obtained per trial), therefore the time variable changed depending on the response variable being tested. Trial number was used for approach time, bait time, and number of approaches per trial, whereas approach number was used for the number of interactions per approach, and interaction number was used for the distance. Four months elapsed between the field trips and different sharks were observed during each trip, so the PPMCCs were calculated independently for each trip. A PPMCC between the response variables and the respective time variable of ±0.9–1, 0.7–0.9, 0.5–0.7, 0.3–0.5, and 0–0.3 was considered as a very strong correlation, a strong correlation, a moderate correlation, a weak correlation, and negligible correlation, respectively.

The proportion of baits taken by sharks was compared using the minlike two-sided Poisson exact test from the *exactci* R package (R statistical software, Ver. 2.13.1) (R Development Core Team, 2011) (Fay, 2010). The minlike two-sided method was chosen because it is generally more powerful than the central two-sided method (Fay, 2010).

Pseudo-replication was managed by testing the effects of the deterrent for all other response variables using a Generalised Linear Mixed-Model (GLMM) through the functions with individual shark as the 'random effect' and the deterrent operational status as the 'fixed effect'. This could not be undertaken for the proportion of baits taken due to the small sample size. The error structure of GLMM corrects for non-independence of statistical units due to shared temporal structure, and permits the 'random effects' variance explained at different levels of clustering to be decomposed. The inclusion of individual shark as a random effect enabled the analysis to account for the lack of independence in behaviour within each identified shark. Each approach or interaction for which shark identification could not be determined was excluded from this analysis. The most appropriate statistical family and error distribution for each analysis was determined through the examination of the distribution of the response variable, a visual inspection of the residuals for the saturated models, and the Akaike Information Criteria value (measure of the relative goodness of fit of a statistical model) (Burnham and Anderson, 2002) when available (depending on the R function used between glmmPQL - library MASS, lmer - library lme4, and glmmML - library glmmML).

Finally, the effects of the deterrent were tested by comparing the distributions of the minimum distance recorded for each interaction using a Kolmogorov-Smirnov (K-S) test

(Massey, 1951) and by comparing the proportion of interactions within 2 m using the minlike two-sided Poisson exact test from the *exactci* R package.

3.1.5 Assessment of the potential behavioural responses to the deterrent at a small spatial scale – (a) Vemco Radio-Acoustic Positioning System

A Vemco Radio-Acoustic Positioning (VRAP) system (VEMCO Ltd., Halifax, Canada) was deployed off North Neptune Islands to determine if the deterrent impacts the behaviour of sharks at spatial scales of >20 m; i.e. outside the spatial scale of the static bait experiments. This component of the project was undertaken to address the question of whether sharks already within the area are attracted to the deterrent from a certain distance prior to being repelled by it at a short distance.

The VRAP consisted of three surface buoys deployed in a near equilateral triangle (distances between buoys ranged from 0.324 to 0.340 km, area = 0.052 km^2) and a shore station in line-of-sight. The locations and distance between the buoys were chosen to ensure that all three hydrophones could detect sharks located in the middle of the array, taking into account environmental noise caused by adverse weather or organisms such as snapping shrimp, and to minimise exposure to extreme weather. O'Dor et al. (1998) and Klimley at al. (2001) provide a detailed description of how the VRAP system estimates the position of tagged organisms. In summary, each buoy is equipped with a multi-directional hydrophone which detects pulses emitted by the transmitters. The received information is transmitted to the shore station via radio signals where the position of each transmitter is calculated based on the arrival times of the acoustic pulses to each buoy and triangulates the latitude and longitude of each animal fitted with an acoustic transmitter. As the transmitters were also fitted with a pressure sensor, the depth was also recorded by the buoys.

The precision of the estimated locations can be up to ±1 m (Zamora and Moreno-Amich, 2002; Barnett et al., 2010). The precision of calculated positions in the current study was also high, with the deployment of sentinel transmitters following the deployment of the VRAP showing a similar level of accuracy within our system.

The shore station was powered by a 167Ah gel battery and two Solar-E 80W solar panels installed with a Powerstar 12 V 20A regulator. Following the first deployment, which required frequent recharging of the batteries (every one to two weeks), solar panels were installed on the buoys, which prevented the need to recharge them. Buoys were powered by one Solar-E 20W solar panel installed with a Morningstar 4.5A regulator. Due to the remote location of North Neptune Islands and the logistical difficulties involved in getting to the shore station, the working order of the equipment was only checked every 1–2 months.

The buoy positions were calibrated by the VRAP at the start of each deployment. Further calibration of the buoy positions after the initial calibration was unnecessary as the buoys were securely moored and unlikely to be moving. This also increased the time the shore station listened for the transmitters rather than re-calibrating at regular intervals. The VRAP was set to listen to each selected frequency for 10 seconds with the number of frequencies selected at any one time ranging from one to nine. The ten-second listening period for each transmitter was, consequently, repeated about every 10 to 90 seconds depending on the number of transmitters selected at the time.

Sharks were tagged with continuous acoustic transmitters (VEMCO Ltd., Halifax, Canada) between the 13th of December 2009 and the 11th of September 2011. Transmitters recorded depth via a calibrated pressure sensor. Transmitters were V16P-5H programmed to transmit every about 1 second and had a predicted battery life of about 50 days. Transmitters were glued to a small anti-fouled net float with waterproof Araldite to ensure that transmitters would remain above the shark's skin and reduce the likelihood of any potentially harmful effects of friction. The net float was tethered to a plastic umbrella dart Domeier™ tag using a 10–15 cm long, 1 mm thick stainless wire trace. Transmitters were implanted using a pole and stainless steel applicator in the dorsal musculature of sharks that were attracted to the vessel with berley independently from the experiments.

A Pearson's goodness-of-fit test was undertaken to assess whether the percentage of detections within specific distances from the berleying vessels (0–29, 30–59, 60–89, 90–119, and > 120 m) changed when the deterrent was activated. These percentages were also tested against periods during which trials were not being undertaken. Although no trials were carried on during those periods, the berley vessels and bait were still present to maintain sharks' interest towards the vessel as part of normal cage-diving operations.

3.1.6 Assessment of the impact of the deterrent on a large spatial scale – (b) presence/absence experiments

Due to the limited data obtained by the VRAP system (see results), further analysis was undertaken using data collected by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), during a study that aimed to assess the effects of berleying on the distribution and behaviour of white sharks (Bruce and Bradford, 2011). As part of this project, ten acoustic receivers (VR2W and VR3-UWM) were deployed at North Neptune Islands over two consecutive periods between December 2009 and April 2011, encompassing two of the three trips undertaken to test the effects of the deterrent. This was also complemented by an existing, iridium satellite-linked acoustic receiver (VR4-Global [VR4G]; Vemco-Amirix Ltd, Halifax, Canada) which has been maintained within the main island's bay since 1 April 2008 (Bradford et al., 2011). Sharks were tagged with coded V16-6H in a similar way to the continuous transmitters, but without a net float and using a metal dart head instead of an umbrella plastic dart.

For each shark present during the experiment, the number of coded acoustic detections during days (four, three, and two days during Trip 1, 2, and 3, respectively) and times (8:00–18:00 hrs) when the experiments were running was averaged as the number of detections/day. These were then compared to the number of detections/day averaged over the two days directly prior and after the trips were undertaken. A oneway-ANOVA was used to test if the number of detections/day during the experiments was different to the days prior or after the experiments.

3.2 Dynamic bait experiments

3.2.1 Study site

The dynamic bait experiments were conducted off Seal Island, in False Bay, south of Cape Town, in the Western Cape region of South Africa (Figure 4). Seal Island is the second largest Cape fur seal (*Arctocephalus pusillus pusillus*) breeding colony in South Africa, and the largest island colony (between 36 000 and 77 000 individuals depending on the time of the year) (Kirkman et al., 2007). The ocean floor off the southern and western sides of the island descends quickly to depths > 20 m, while on the northern and eastern sides, the slope is more gradual. The waters surrounding the island support large numbers of white sharks from May through September (Hammerschlag et al., 2006; Laroche et al., 2008). This site was chosen because it has a high recorded rate of predatory behaviour of white sharks on pinnipeds (Laroche et al., 2008). At this location, sharks are regularly observed to breach out of the water during natural predation events. It was assumed that this breaching behaviour would provide a good opportunity to test the effect of the deterrent when a shark is engaging in predatory behaviour. Such breaching behaviour is regularly elicited by wildlife tourism operators by towing a seal-shaped decoy around Seal Island (Hammerschlag et al., 2006). Furthermore, experimental decoy tows have been successfully used to study Cape fur seal predation risk when moving near Seal Island (De Vos and O'Riain, 2010). Therefore, we undertook experimental tows of a seal decoy to determine if the deterrent reduced the likelihood of a shark interacting with or undertaking breaching behaviour on a seal decoy.

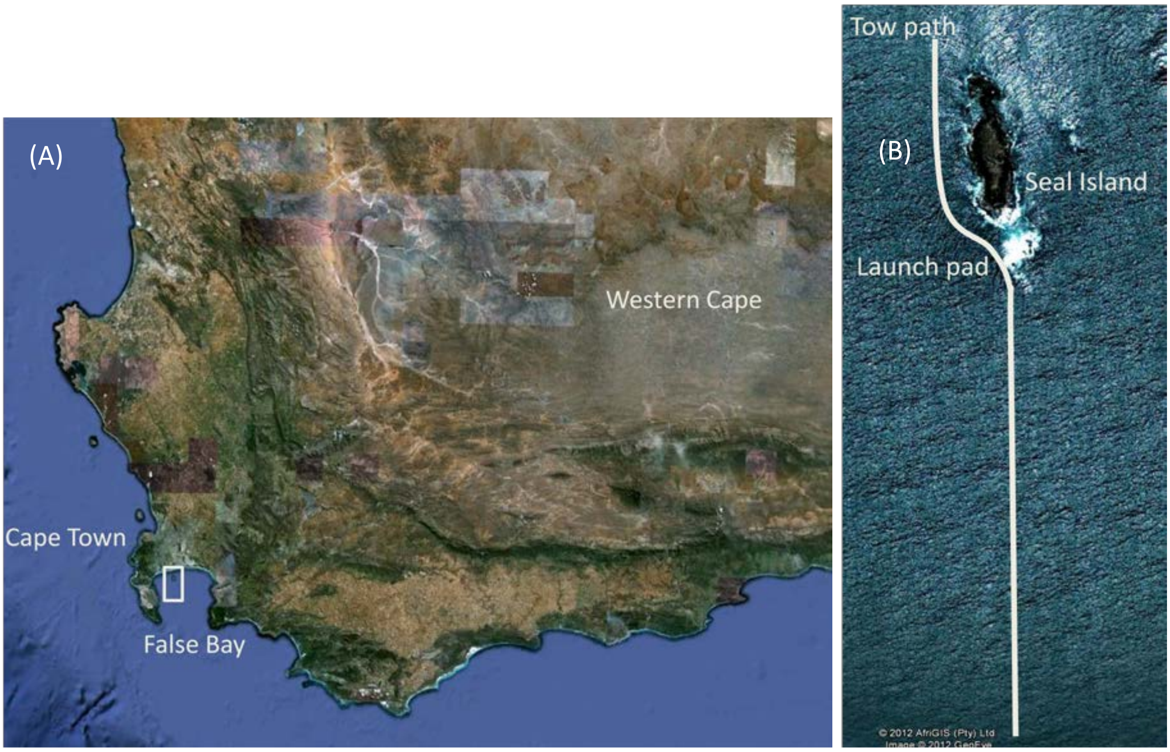

Figure 4. Study location at Seal Island in False Bay, South Africa. (A) shows the region and False Bay, (B) shows Seal Island with the white line representing the path of the tows.

3.2.2 Tows of seal decoy

A fibreglass coated foam seal-shaped decoy was towed 20–25 m behind a vessel at a speed of 8–10 km.hr^{-1}. This speed was chosen based on records of travelling speeds of Cape fur seals leaving Seal Island (De Vos and O'Riain, 2010). Towing was only undertaken when wind speed was less than 15–20 knots. During stronger winds, the seal decoy regularly went underwater making it impossible to tow adequately. To maximise the chance of eliciting a predatory response to the decoys, tow time and route were chosen based on the knowledge that predator-prey activity is spatio-temporally confined and predictable at Seal Island (Laroche et al., 2008). Tows were confined to the sunrise (low light) and mid-morning periods between 6:30–10:00 am and covered the area between 1 km south of Seal Island towards the Island and the southern tip of the island called the “launch pad” (Laroche et al., 2008), to the West about 50–150 m from the Island, and the Northwest area of Seal Island (Figure 5). Tows were 1.7–2 km long and undertaken in both a North and South direction.

The deterrent was affixed to a small black trolling paravane or underwater glider (175 X 75 mm) to ensure that the equipment glided through the water at a suitable angle to record shark approaches and interactions with the decoy. Two 2-pound (907 g) weights were attached to the paravane to bring the deterrent to a water depth of about 180 cm and to prevent the deterrent from streaming along the surface, which could reduce its effectiveness. An underwater camera (GoPro™) was fixed to the paravane to record interactions between sharks and the seal decoy, including those not visible from the surface (e.g. aborted breaches). The deterrent, paravane, and camera were connected to the vessel via 2-mm wire to avoid the loss of the equipment in case of a physical interaction between the equipment and the shark. The seal decoy was linked to the wire by a 1.2-mm diameter nylon fishing line of about 250 cm long. The equipment was configured so that the decoy would be slightly behind the end tip of the deterrent to reduce the potential for visual and/or physical distraction for a shark breaching. The distance between the seal-decoy and the deterrent was about 210 cm.

Prior to each experimental tow, the wind direction and speed, cloud cover, and swell height were estimated and the water visibility was measured using a secchi disk. During each tow, the following data and observations were recorded: the start and end locations, duration of the tow, breaches and/or investigations, and other seal and shark activities.

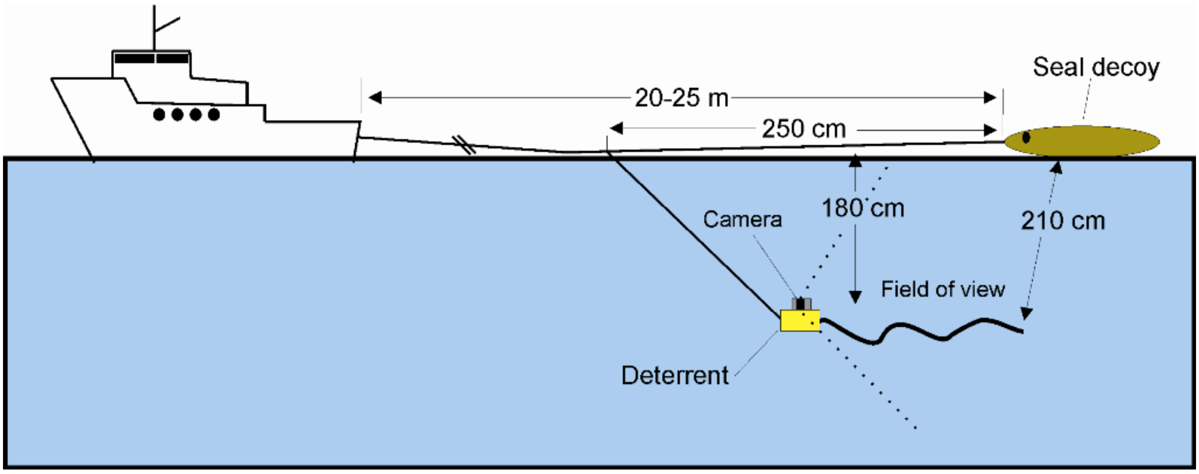

Figure 5. Schematic representation of the experimental set-up used to test the deterrent on dynamic bait (seal decoy) at Seal Island off the coast of South Africa.

3.2.3 Selection of shark interactions and data coding

All digital recorded footage collected during the dynamic bait experiment was reviewed by CH. Following the first year of towing, the video footage was also independently reviewed by another scientist to ensure that CH was not missing interactions. CH recorded 34 interactions and the other scientist observed 31 of the same plus one interaction that was not recorded by CH. The four interactions that were not detected by both scientists were of very poor quality due to the sharks remaining away from the camera and decoy. As a result, the behaviour of sharks during these interactions could not be determined and all interactions close enough for behaviours to be determined were recorded by both scientists. Footage from the second year of towing was only reviewed by CH. Once the interactions were identified from the video footage, they were isolated and clipped with Camtasia Studio 7.0 (TechSmith, Okemos, Michigan, USA) for further coding. Out of those clipped portions of the footage, interactions during which shark behaviour could not be determined (e.g., due to low visibility, distance of the shark, and framing) were discarded to remove any ambiguous interactions. Each interaction was categorised as:

- A *breach*: A breach is defined as an interaction during which a shark leaps out of the water, with several subtypes described by Martin et al (2005) (Supplementary electronic information C, D, Figure 6a);
- A *surface interaction*: interactions during which sharks did not leap out of the water but during which dorsal or caudal fins were visible above the water such as during lateral roll, surface arc, direct or surface approach in Martin et al (2005) (Supplementary electronic information E, Figure 6b); or

- An *underwater interaction*: interactions were not visible from the surface (Supplementary electronic information F).

Seven scientists not present during the trials further coded each recorded interaction, based on the underwater footage, into either investigation, breach, or aborted breach, and assessed whether each approach concluded with a sudden change of direction (potential response to an activated deterrent, categorised as ‘yes’, ‘no’, or ‘unsure’) (Supplementary electronic information G, H).

- An *investigation* was defined as any interaction during which a shark approached the decoy at a slow speed or at a vertical angle of less than 30° (Supplementary electronic information I). Speed was assessed using the time between shark appearance on the footage and when it got within 2 m of the seal decoy. Angle of approach was estimated by looking at the angle difference between the shark body and the water surface when 2 m away from the seal decoy.
- A *breach* was defined as when a shark approached the decoy with speed and at an angle of more than 30°, and finished the approach by leaping partially or completely out of the water (Supplementary electronic information C, D).
- An *aborted breach* was defined as when a shark approached the decoy with speed and at an angle of more than 30° within 3 m, but did not complete the approach and did not breach the water surface (Supplementary electronic information J).

Additionally, the level of confidence in the coding was recorded using a three-level confidence scale from one to three with one indicating a small amount of confidence in the coding assigned and three indicating a high level of confidence. To avoid including the interactions where coders were not confident in their interpretation or where coders disagreed, any coding data obtained with a confidence rating of one or with less than 70% agreement between coders, were excluded from the analysis.

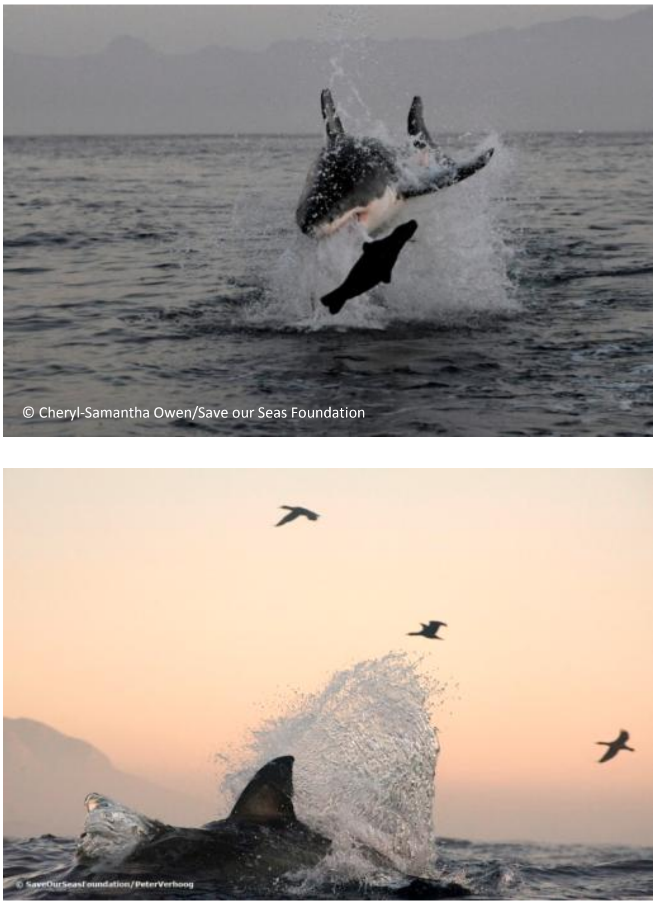

Figure 6. Example of (a) breach and (b) surface interaction.

3.2.4 Data analysis

The efficacy of the activated deterrent in repelling white sharks from attacking a towed seal decoy was assessed by comparing the number of breaches, surface interactions, underwater interactions, and total number of interactions using the minlike two-sided Poisson exact test from the *exactci* R package (Fay, 2010). The proportion of breaches, aborted breaches and investigations coded and the proportion of interactions to include a reaction to an activated deterrent were also tested using the same minlike two-sided Poisson exact test. While the results are provided for each year independently and for years combined, statistical tests were only undertaken on data combining both years due to the limited number of interactions during individual years.

For all statistical analyses (for static and dynamic experiments), $P<0.05$ was considered statistically significant.

4. RESULTS

4.1 Static bait experiment

A total of 116 trials were completed, with 28, 64, and 24 during Trips 1, 2, and 3, respectively. Of these, 49 trials were done with the deterrent turned off (16, 25, and 8 during Trips 1, 2, and 3, respectively) and 67 with it turned on (12, 39, and 16 during Trips 1, 2, and 3, respectively). A total of 314 approaches and 527 interactions by 18 different white sharks were observed. Most sharks approached the bait and equipment during trials when the deterrent was both off and on. Out of the three trips, four sharks were observed only when the deterrent was turned on while one shark was only observed when the deterrent was turned off. Individual identification of white sharks was generally possible, but could not be made during 132 approaches (42%) and 179 interactions (34%). Many of the individual sharks interacted with the bait and the deterrent on several occasions, with the number of trials during which an identified shark interacted with the deterrent ranging from 1 to 27 (mean ± standard deviation: 6.89 ± 7). The number of approaches per identified shark ranged from 1 to 40 (10.11 ± 10), while the number of interactions per identified shark ranged from 1 to 71 (19.33 ± 21) (Table 2). During a single trial, the maximum number of approaches, interactions, and interactions per approach was 12, 29, and 18, respectively.

4.1.1 Temporal correlations

The behaviour of the sharks did not seem to change over time as little or no temporal correlation (0–0.3) was found during each trip or for any response variable (Table 3). The strongest correlations (-0.25 and -0.3) occurred during Trip 3 and were for bait time and the number of approaches per trial. This suggested that during the third Trip, sharks were taking the bait slightly faster and undertaking slightly fewer approaches as the trials were being undertaken. These correlations, however, were weak.

Table 2. Number of trials, approaches, and interactions during which sharks of known identity were observed.

Shark	# of trials	Approaches	Interactions
1	9	10	20
2	8	17	22
3	27	40	67
4	14	25	39
5	13	17	71
6	1	1	2
7	11	12	21
8	4	5	19
9	1	1	1
10	9	18	23
11	1	1	8
12	3	3	3
13	11	13	17
14	4	6	7
15	1	1	3
16	2	3	12
17	1	1	1
18	4	8	12
Unknown	61	132	179
Total	185	314	527

Table 3. Summary of Pearson product-moment correlation coefficients for each response variable.

Response variable	Trip 1	Trip 2	Trip 3
Approach time	-0.153	-0.041	-0.174
Bait time	-0.182	-0.011	-0.247
Approaches per trial	0.013	0.001	-0.300
Interactions per approach	0.034	0.001	0.001
Distance	-0.114	0.037	-0.175

4.1.2 Effects of the deterrent on the behaviour of white sharks

The bait was taken within the 15-minute period during 78% of the trials, with the deterrent not affecting the likelihood of the baits being taken. There was no significant difference between the proportion of bait taken when the deterrent was turned off or on, regardless of the trips being combined (Poisson exact test: p=1.00) or separated (Poison exact test: Trip 1: p=0.60; Trip 2: p=0.89; and Trip 3: p=0.82) (Table 4).

Table 4. Summary of the results obtained from the static bait experiment. SE represents standard error; Distance is the minimum distance between a shark and the deterrent measured for each interaction. This table summarises all data recorded, included for unidentified sharks.

	Trip 1			*Trip 2*			*Trip 3*			*Total*		
	OFF	ON	Total	OFF	ON	Total	OFF	ON	Total	OFF	ON	Total
Number of trials	16	12	28	25	39	64	8	16	24	49	67	116
Number of sharks	2	2	3	9	12	12	3	4	4	14	17	18
Number of approaches	19	14	33	54	162	216	20	45	65	93	221	314
Number of interactions	27	23	50	65	324	389	29	59	88	121	406	527
Number of baits taken	10	5	15	22	33	55	6	15	21	38	53	91
Percentage of bait taken	62.5%	41.7%	53.6%	88.0%	84.6%	85.9%	75.0%	93.8%	87.5%	77.6%	79.1%	78.4%
Mean Approach time (sec)	168	119	151	88	67	75	94	51	66	112	69	87
SE Approach time (sec)	65	38	44	27	11	75	37	15	66	24	9	12
Mean Bait time (sec)	222	244	229	133	248	202	173	196	189	163	233	204
SE Bait time (sec)	82	87	60	27	36	25	82	64	50	29	30	21
Mean Approaches/trial	1.46	2.00	1.65	2.16	4.15	3.38	2.50	2.81	2.71	2.02	3.56	2.91
SE Approaches/trial	0.31	0.38	0.24	0.27	0.51	0.35	0.60	0.59	0.44	0.20	0.37	0.24
Mean Interactions/approach	1.42	1.64	1.52	1.20	2.00	1.80	1.45	1.31	1.35	1.30	1.84	1.67
SE Interactions/approach	0.19	0.31	0.17	0.06	0.16	0.12	0.15	0.08	0.07	0.06	0.12	0.09
Mean Distance	1.35	1.94	1.63	2.54	2.81	2.76	1.96	2.19	2.12	2.13	2.67	2.55
SE Distance	0.33	0.34	0.24	0.30	0.11	0.11	0.35	0.27	0.22	0.20	0.10	0.09

Out of the 18 individually identified sharks that interacted with the bait, 14 (78%) removed baits from the floats. While at least eight individuals (44%) took the bait when the deterrent was turned off, 13 (72%) took the bait when the deterrent was turned on. Among these, six sharks only took the bait when the deterrent was turned on and one shark only took the bait when the deterrent was turned off. The remaining seven sharks took the bait both when the deterrent was both turned off and on. Six sharks took the bait on several occasions, with one shark (Shark 3) taking the bait a total of 23 times including 14 times when the deterrent was turned on. The shark responsible for taking the bait could not be identified on 15 occasions (16%) (Table 5).

Table 5. Number of trials during which a white shark took the bait within the 15-minute period.

Shark	OFF	ON	Total
1	2	4	6
2	-	1	1
3	9	14	23
4	7	4	11
5	4	3	7
6	-	1	1
7	3	8	11
8	1	1	2
9	-	1	1
10	-	-	-
11	-	1	1
12	-	1	1
13	2	7	9
14	-	1	1
15	-	-	-
16	1	-	1
17	-	-	-
18	-	-	-
Unknown	9	6	15
Total	38	53	91

Out of the remaining five response variables used to assess the effects of the deterrent (i.e. approach time, bait time, approach per trial, interaction per approach, and distance), the time it took to take the bait, number of interaction per approach, and the minimum distance between sharks and the deterrent were significantly different when the deterrent was activated. Additionally, the random factor (individual sharks) was also significantly different for all parameters (Table 6) indicating that there were variations in behaviour between individual sharks.

Table 6. Generalised Linear Mixed-Model result summary. DF represents degree of freedom.

Parameters analysed	DF	Shark ID (intercept)		Deterrent	
		t	P	t	P
Approach time	49	3.86	<0.001	-0.17	0.87
Bait time	61	5.54	<0.001	-2.58	0.01
Approach per trial	105	9.52	<0.001	0.87	0.38
Interaction per trial	163	2.42	0.02	3.66	<0.001
Distance	292	8.25	<0.001	2.6	0.01

Once the experimental equipment was deployed, sharks first approached the bait rapidly (80 ± 11 seconds, mean ± standard error - SE). The deterrent did not affect the speed at which sharks first appeared and approached the bait. There was no significant difference in the time it took sharks to first be sighted whether the deterrent was turned off (77 ± 21 seconds, mean ± SE) or on (82 ± 12 seconds, mean ± SE) (GLMM (Gamma, inverse): t_{49}=-0.17, P=0.87) (Figure 7).

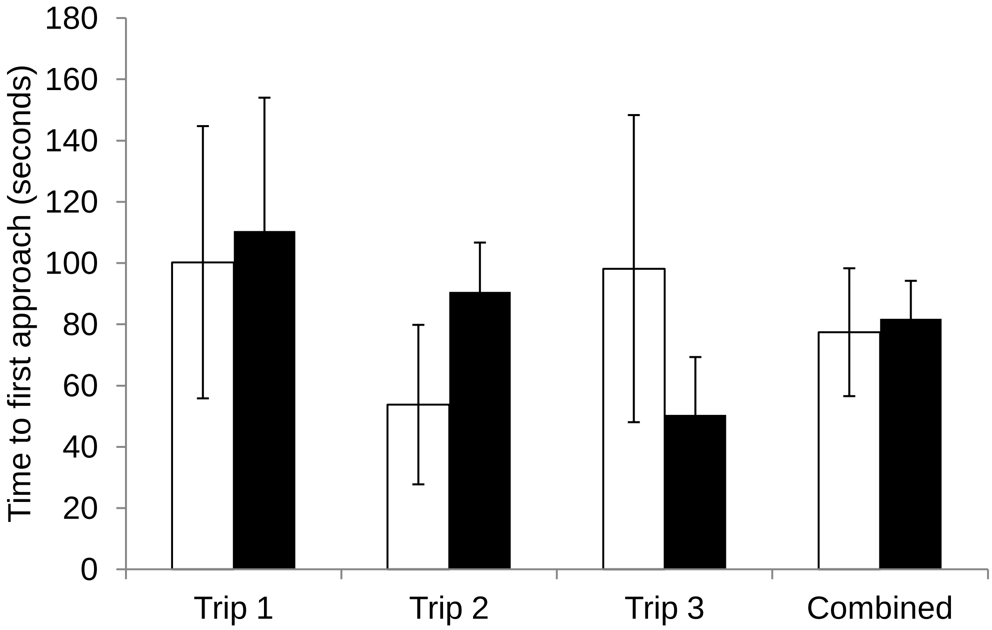

Figure 7. Number of seconds before a white shark first approached the deterrent was turned off or on for each trip separately and for trips combined. White bars represent trials with the deterrent turned off; black bars represent trials with the activated deterrent; error bars represents standard error.

On average it took 197 ± 23 seconds (mean ± SE) from the start of a trial for sharks to take the bait. Although the deterrent did not affect the time it took sharks to be first sighted, sharks took significantly longer to take the bait when the deterrent was turned on (244 ± 32 seconds, mean ± SE) than when it was turned off (122 ± 24 seconds, mean ± SE) (GLMM (Gamma, inverse): t_{61}=-2.58, P=0.01) (Figure 8).

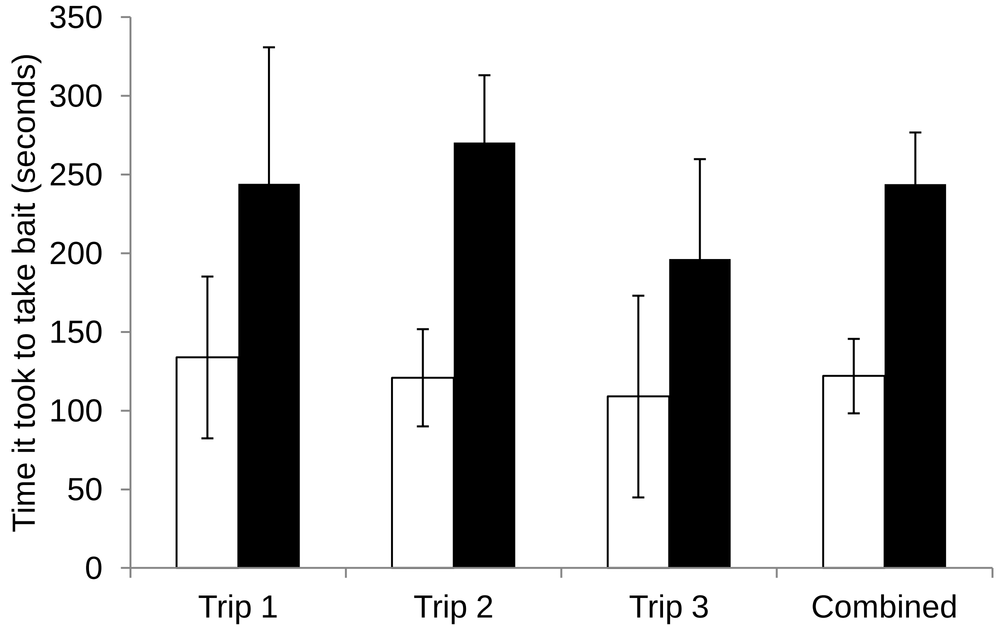

Figure 8. Number of seconds it took white sharks to take the bait when the deterrent was turned off or on for each trip separately and for trips combined. White bars represent trials with the deterrent turned off; black bars represent trials with the activated deterrent; error bars represents standard error.

There was no significant difference in the number of approaches per trial when the deterrent was activated (GLMM (Poisson, identity): t_{105}=0.87, P=0.39) (Figure 9). The number of interactions per approach, however, increased from 1.33 ± 0.08 (mean ± SE) when the deterrent was turned off to 2.20 ± 0.20 (mean ± SE) when the deterrent was turned on (GLMM (Poisson, log): t_{163}=3.66, P<0.001. This suggests that the sharks did not approach the bait more often when the deterrent was activated, but they interacted with the bait more often within each approach (Figure 10). The greatest difference in the number of approaches per trial occurred during Trip 2 and was mostly driven by one shark for which the number of approaches quadrupled when the deterrent was activated.

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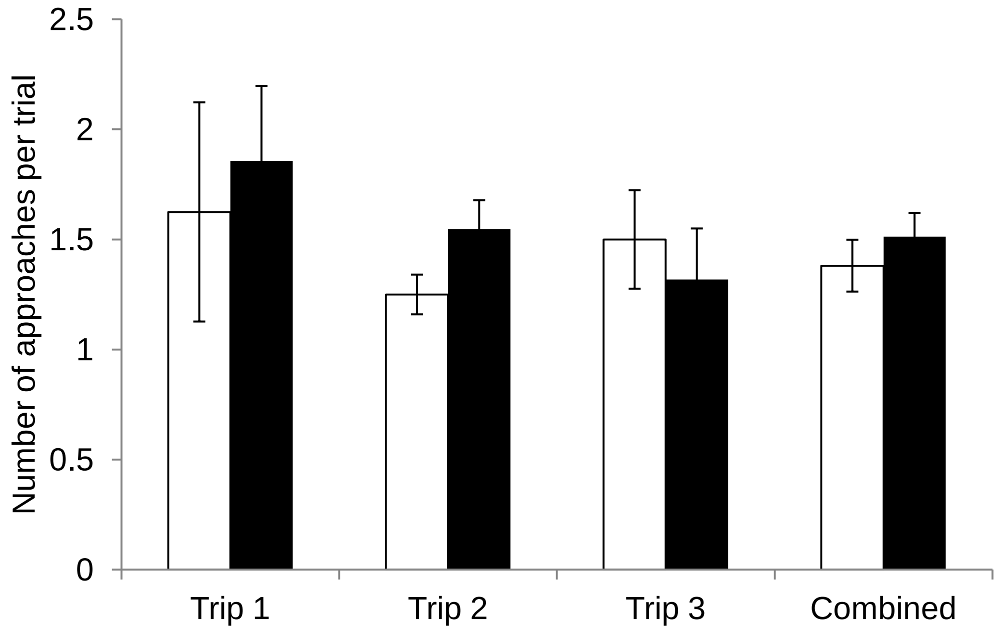

Figure 9. Number of approaches per trial when the deterrent was turned off or on for each trip separately and for trips combined. White bars represent trials with the deterrent turned off; black bars represent trials with the activated deterrent; error bars represents standard error.

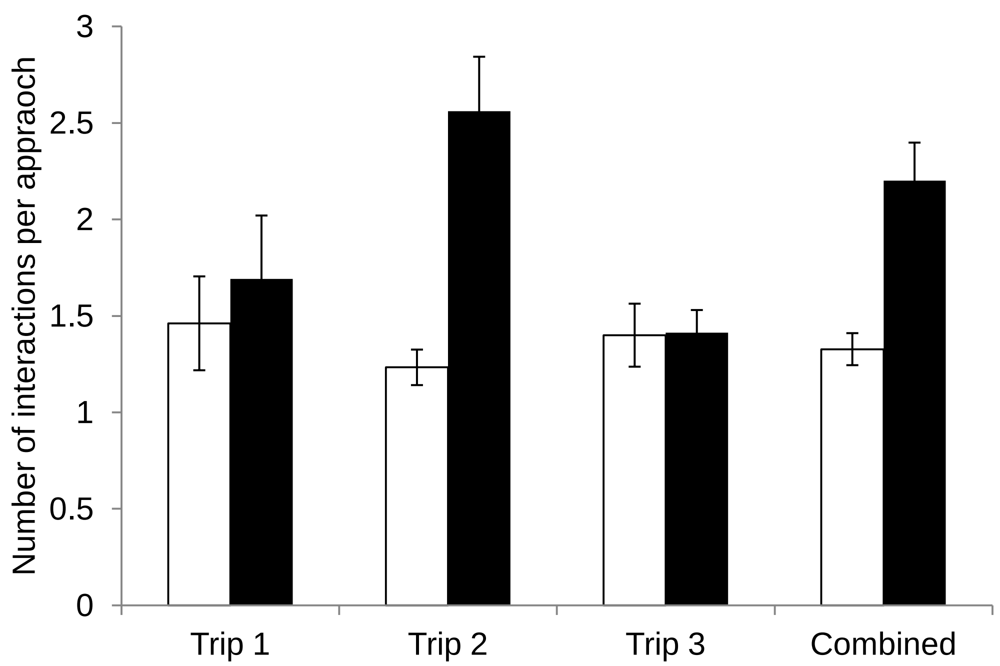

Figure 10. Number of interactions per approach when the deterrent was turned off or on for each trip separately and for trips combined. White bars represent trials with the deterrent turned off; black bars represent trials with the activated deterrent; error bars represents standard error.

Although sharks were still able to take the bait when the deterrent was activated, the deterrent had impacts on the behaviour of the shark and significantly increased the mean minimum distance between the shark and the deterrent from 1.77 ± 0.20 to 2.44 ± 0.11 m (mean ± SE) when activated (GLMM (Gamma, identity): t_{292}=2.60, P=0.01). The greatest difference in the minimum distance occurred during Trip 2 (Figure 11).

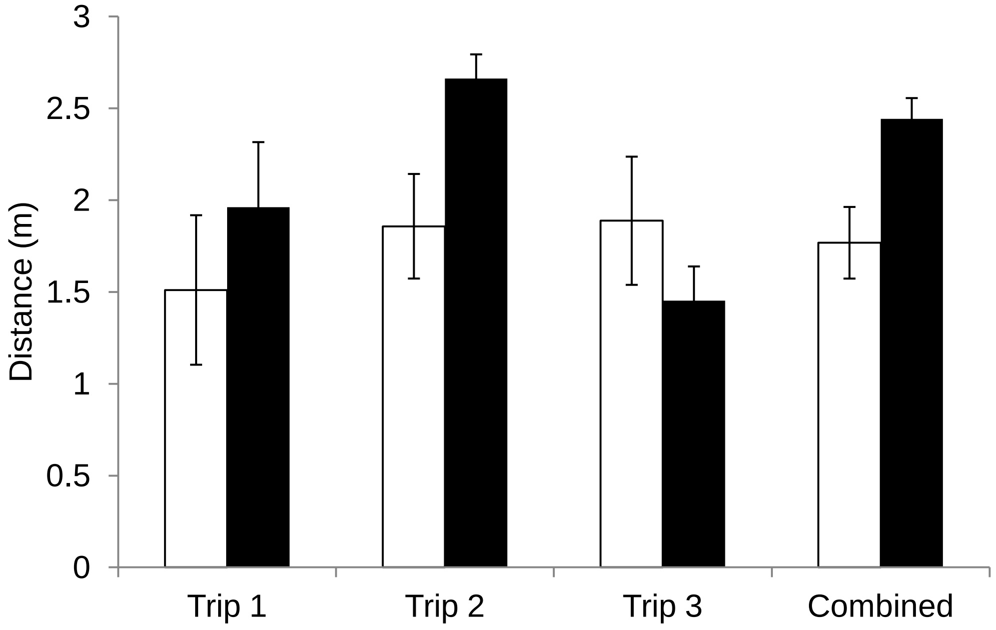

Figure 11. Minimum distance between white sharks and the deterrent bait when the deterrent was turned off and on for each trip separately and for trips combined. White bars represent trials with the deterrent turned off; black bars represents trials with the activated deterrent; error bars represents standard error.

The distribution of the minimum distance between the sharks and the deterrent changed significantly (K-S test: P<0.001), with less interactions being within 2 m of the deterrent when it was turned on (Poisson exact: P=0.0001). This was, again, mostly driven by Trip 2 (K-S test: P=0.02; Poisson exact: P=0.002), because the distribution of the minimum distance was not significantly different whether or not the deterrent was turned on during Trip 1 (K-S test: P=0.06; Poisson exact: P=0.09) or Trip 3 (K-S test: P=0.96; Poisson exact: P=0.51) (Figure 12).

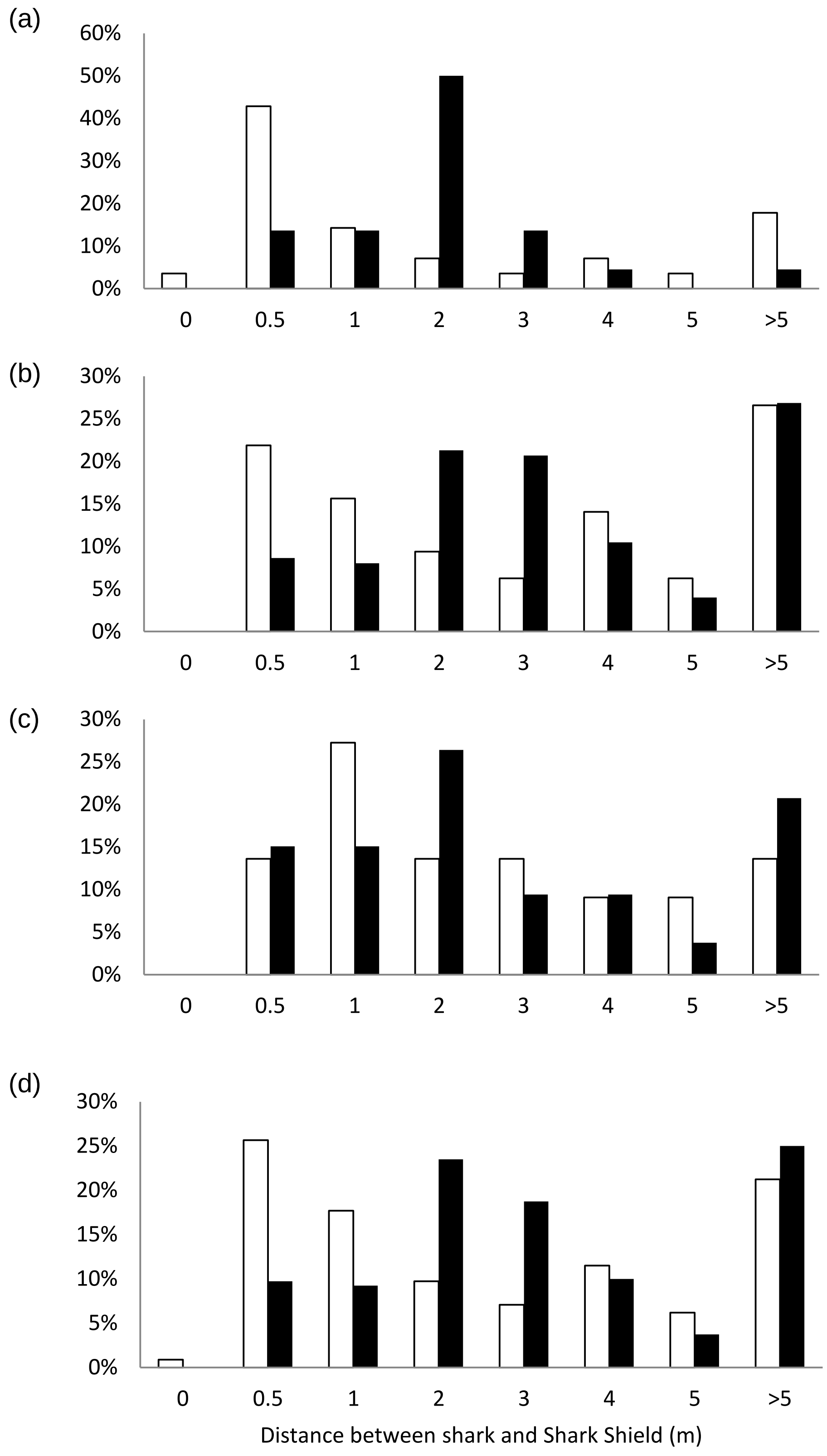

Figure 12. Histograms of the minimum distance between white sharks and the deterrent for each interaction when it was turned off (white bars) and turned on (black bars) during (a) Trip 1, (b) Trip 2, (c) Trip 3, and (d) all trips combined.

4.1.3 Assessment of the impact of the deterrent on a large spatial scale – (a) VRAP component

Between November 2009 and September 2011, the VRAP system was deployed at the same location for three monitoring periods ranging from 96 to 187 days each. During these periods, 21 white sharks were tagged with acoustic transmitters. Two, ten, and nine sharks were tagged and monitored during the three deployment periods, respectively. White sharks were detected within the monitored area for 1 (Shark 6, 7, 8, and 11) to 17 days (Shark 21) (mean ± standard error = 3.5 days ± 0.9) while no locations were estimated for three of the 21 tagged sharks (Shark 2, 12, and 15). A total of 22,329 locations were calculated, with the number of locations estimated per shark ranging from 2 (Shark 7) to 6,116 (Shark 21) (mean ± standard error = 1,063 ± 333.6) (Table 7).

Table 7. Summary of tagged sharks and detections. TL is estimated total length; location estimates is the number of location estimates recorded by the VRAP system.

Shark	TL (mm)	Sex	Date tagged	Last transmission	Days detected	Location estimate
1	3600	Male	14/12/2009	15/12/2009	2	413
2*	3500	Male	18/01/2010	18/01/2010	0	0
3	3300	Female	26/06/2010	27/06/2010	2	641
4	3000	Female	27/06/2010	29/06/2010	3	418
5	4500	Female	27/06/2010	29/06/2010	3	182
6	2500	Female	17/08/2010	17/08/2010	1	5
7	4200	Female	17/08/2010	17/08/2010	1	2
8	4000	Male	4/10/2010	4/10/2010	1	7
9	4000	Male	14/10/2010	1/11/2010	12	3830
10	3500	Male	22/10/2010	2/11/2010	5	2714
11	3800	Male	22/10/2010	22/10/2010	1	11
12*	4200	Male	12/12/2010	12/12/2010	0	0
13	4500	Female	5/07/2011	7/07/2011	3	1466
14	2900	Male	5/07/2011	7/07/2011	3	576
15*	4000	Male	6/07/2011	6/07/2011	0	0
16	3600	Male	6/07/2011	7/07/2011	2	1263
17	3800	Female	6/07/2011	7/07/2011	2	771
18	2800	Male	6/07/2011	7/07/2011	2	1339
19	3500	Female	11/09/2011	30/09/2011	4	798
20	4000	Male	11/09/2011	26/09/2011	9	1777
21	4200	Male	11/09/2011	28/09/2011	17	6116

* sharks not detected by VRAP array

The effects of the deterrent on the behaviour of sharks could only be tracked by the VRAP during Trip 3 due to logistical limitations and weather conditions. None of the sharks tagged prior to or during Trip 1 were present or detected when trials were being undertaken. During Trip 2, while tagged sharks were present and interacted with the equipment deployed, the strong southeast wind conditions prevented trials from being undertaken in the VRAP array. Weather conditions allowed trials during Trip 3 to take place in the VRAP array, and a total of 3,984 location estimates from six sharks (mean 797, range 423–1103 location estimates per shark) were obtained. Five hundred and thirteen of these location estimates were obtained at night and were removed from further analysis. Of the remaining location estimates, 121 and 179 were obtained when the deterrent was turned off and on, respectively.

Based on the data obtained from the VRAP, the proportion of detections in close proximity to the experimental vessel (0–60 m) significantly decreased from 60% when the deterrent was turned off to 42% when it was turned on (χ^2=12.62; P=0.013). The location estimates obtained when trials were not undertaken, however, were also significantly different to the data obtained during trials with the deterrent turned off (χ^2=12.48; P=0.014) (Figure 13).

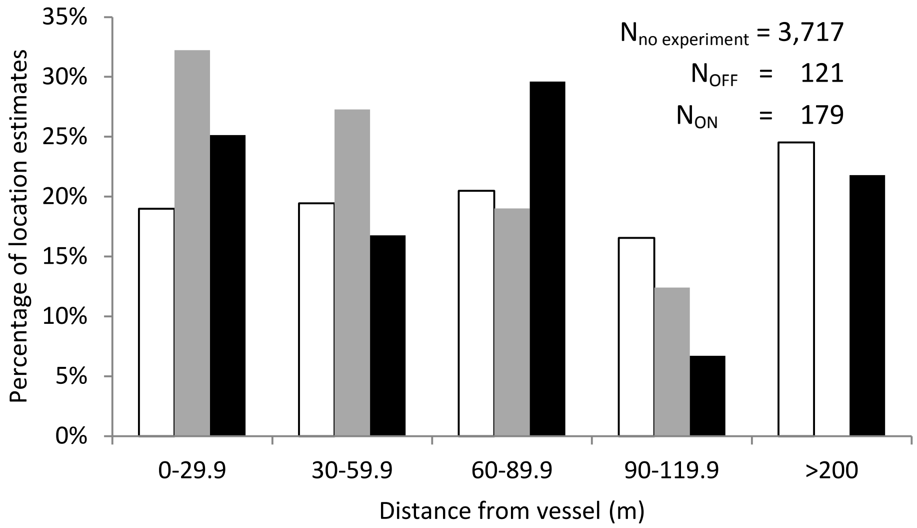

Figure 13. Percentage of locations estimated according to the distance between tagged white sharks and vessels from which trials were undertaken. White bars represent periods during which no trials occurred; grey bars represent periods during which the deterrent was turned off; black bars represent periods during which the deterrent was turned on; N represents number of location estimates obtained per grouping. Location estimates were all obtained during Trip 3.

4.1.4 *Assessment of the impact of the deterrent on a large spatial scale – (a) presence/absence component*

An additional 12 sharks (nine males, one female, two unknown, ranging from 3.2–4.5 m total length) were tagged with coded acoustic transmitters and were detected before, during, and after the trials being undertaken. A total of 8,464 detections of tagged sharks were obtained, with 4,701 of these detections recorded during the deterrent trials. Although slightly more detections were obtained during the days when the trials took place (1017 detections/day – 43%) than before (951 detections/day – 40%) or after (408 detections/day – 17%) the trials (Figure 14), this was not significantly different (ANOVA: $F_{2,33}$=1.96; P=0.16).

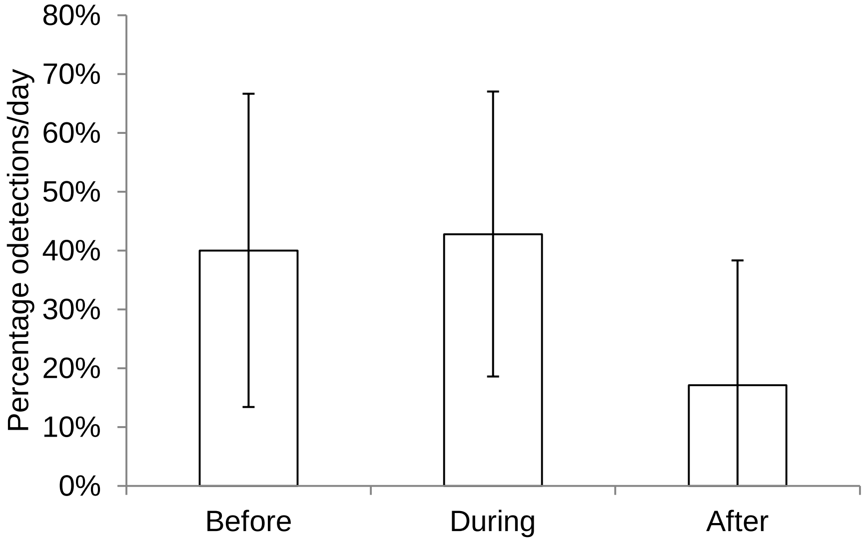

Figure 14. Percentage of detections of 12 acoustically tagged white sharks obtained prior, during, and after the deterrent trials. Error bars represent standard deviation.

4.2 Dynamic tows

A total of 190 tows were undertaken in July and August 2010 (94 tows) and 2011 (96 tows). Of these, 98 tows were undertaken with the deterrent turned off (47 in 2010, 51 in 2011) and 91 with the deterrent turned on (47 in 2010, 44 in 2011). Tows occurred over 37 hours 39 minutes (19 hours 06 minutes with the deterrent turned off, 18 hours 2 minutes with the deterrent turned on) with each tow lasting an average of 11 minutes 44 seconds. Towing took place on 22 days (11 days in each 2010 and 2011). Due to logistical difficulties such as the electrodes wrapping around the equipment, poor visibility, and lack of light penetrating through the water surface, video footage was only obtained from 169 tows (74 in 2010 and 95 in 2011). Of these, 86 videos were taken with the deterrent turned off (35 in 2010, 51 in 2011) and 83 with the deterrent turned on (39 in 2010, 44 in 2011) (Table 8).

Sixty-one interactions, 43 with deterrent off, 18 with deterrent on, between a shark and the decoy were recorded when surface and underwater interactions were combined. Of these, 35 interactions occurred in 2010 (23 with deterrent off, 12 with deterrent on) and 26 in 2011 (20 with deterrent off, 6 with deterrent on). Interactions visible from the surface (e.g., breach, aborted breach close to decoy, lunge, swimming on the surface behind the decoy) accounted for 29 of the 61 interactions observed (27 with deterrent off, 2 with deterrent on). Of these, 18 interactions occurred in 2010 (17 with deterrent off, 1 with deterrent on) and 11 in 2011 (10 with deterrent off, 1 with deterrent on). Sixteen breaches occurred during the tows (9 in 2010 and 7 in 2011) with all breaches occurring when the deterrent was turned off (Table 8).

Taking into account the number of tows undertaken and suitable videos available, the number of interactions per tow across all experiments was 0.33 and decreased from 0.44 to 0.22 when the deterrent was turned on. While the number of surface interactions per tow decreased from 0.28 to 0.02 when the deterrent was turned on, the strongest effects of the deterrent was recorded for breaches, with no breach observed when the deterrent was turned on (Table 8, Figure 15).

Table 8. Summary of the number of tows and interactions obtained when testing the deterrent on a dynamic decoy in South Africa.

	2010			2011			TOTAL		
	OFF	ON	Total	OFF	ON	Total	OFF	ON	Grand total
Tow duration (mean)	0:11:49	0:12:01	0:11:55	0:11:35	0:11:29	0:11:32	0:11:42	0:11:46	0:11:44
Total duration of towing	9:15:44	9:25:06	18:40:50	9:50:42	8:37:07	18:27:49	19:06:26	18:02:13	37:38:39
N° of tows	47	47	94	51	44	95	98	91	189
N° of videos	35	39	74	51	44	95	86	83	169
N° of breaches	9	0	9	7	0	7	16	0	16
N° of surface interaction	17	1	18	10	1	11	27	2	29
N° of total interactions	23	12	35	20	6	26	43	18	61
N° of breach/tow	0.19	0.00	0.10	0.14	0.00	0.07	0.16	0.00	0.08
N° of surface interaction/tow	0.36	0.02	0.19	0.20	0.02	0.12	0.28	0.02	0.15
N° of interaction on video	18	12	30	20	6	26	38	18	56
N° of interaction on video/video	0.51	0.31	0.41	0.39	0.14	0.27	0.44	0.22	0.33

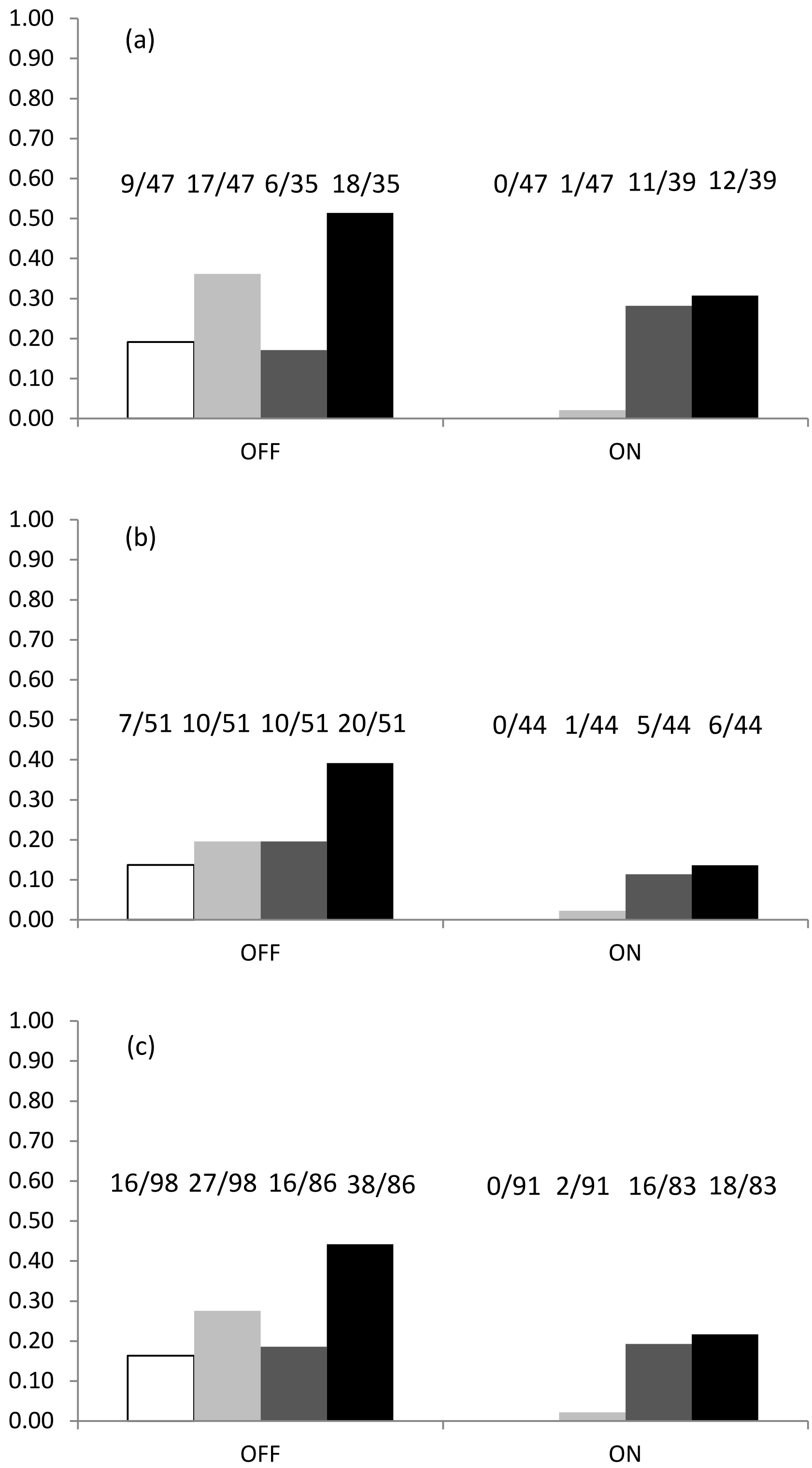

Figure 15. Proportion of breaches/tow (white), surface interactions/tow (light grey), underwater interactions/video (dark grey), and total number of interactions recorded (surface and on video)/video (black) for 2010 (a), 2011 (b), and years combined (c) compared when the deterrent was turned off or on. Numbers above bars indicate the number of events per replicate.

The number of breaches per tow, surface interactions per tow, and total number of interactions recorded were significantly less when the deterrent was turned on compared to when the deterrent was turned off (Table 8, Figure 15, $p < 0.001$). The number of underwater interactions per video, however, did not change significantly whether the deterrent was turned on or off ($P = 1.00$).

Fifty-six interactions, 38 vs. 18 when the deterrent was turned off and on, respectively, were detected in the underwater camera footage, and 47 interactions (32 vs. 15 when the deterrent was turned off and on, respectively) were considered assessable by CH. Additional filtering following coding of the data resulted in 15% of the coding for behavioural approach (7 interactions) and 38% of the coding for change of direction (18 interactions) being removed. There was no difference in the amount of data filtered relative to the operational status of the deterrent for behavioural approach (16% vs. 13% for off and on) and change of direction (37% vs. 40% for off and on).

The proportions of investigations and aborted breaches increased more than two-fold when the deterrent was turned on compared to when it was turned off (from 0.31 to 0.80 and from 0.03 to 0.07 for investigation and aborted breach, respectively). While the proportion of investigations were significantly different when the deterrent was turned on from when it was turned off (Poisson exact test: $p = 0.003$), the proportion of aborted breaches was not significantly different (Poisson exact test: $p = 0.54$) due to the small number of aborted breaches coded (one each when turned on or off). The proportion of breaches decreased significantly from 0.5 to 0.0 (Poisson exact test: $p = 0.04$) when the deterrent was turned on compared to when it was turned off (Table 9, Figure 12). The proportion of interactions where a sudden change of direction (used as a proxy for a reaction to the deterrent) was not observed decreased from 0.59 to 0.27, but was not significantly different (Poisson exact test: $p = 0.18$) when the deterrent was turned on. The proportion of interactions where a sudden change of direction was observed increased significantly from 0.0 to 0.2 (Poisson exact test: $p = 0.03$), while the proportion of interactions where a sudden change was 'unsure' also increased from 0.03 to 0.13, but was not significantly different (Poisson exact test: $p = 0.24$) (Table 9, Figure 17).

Table 9. Summary of the proportion of behaviours per video coded and sudden change of direction (used as a proxy for a reaction to the deterrent) per video coded.

	OFF	ON	Total
Number of video coded	32	15	47
Proportion of behaviour			
Investigation	0.31	0.80	0.47
Aborted approach	0.03	0.07	0.04
Breach	0.50	0.00	0.34
Total behaviour coded	0.84	0.87	0.85
Proportion of sudden change of direction (reaction)			
Yes	0.00	0.20	0.06
No	0.59	0.27	0.49
Unsure	0.03	0.13	0.06
Total 'Reaction' coded	0.63	0.60	0.62

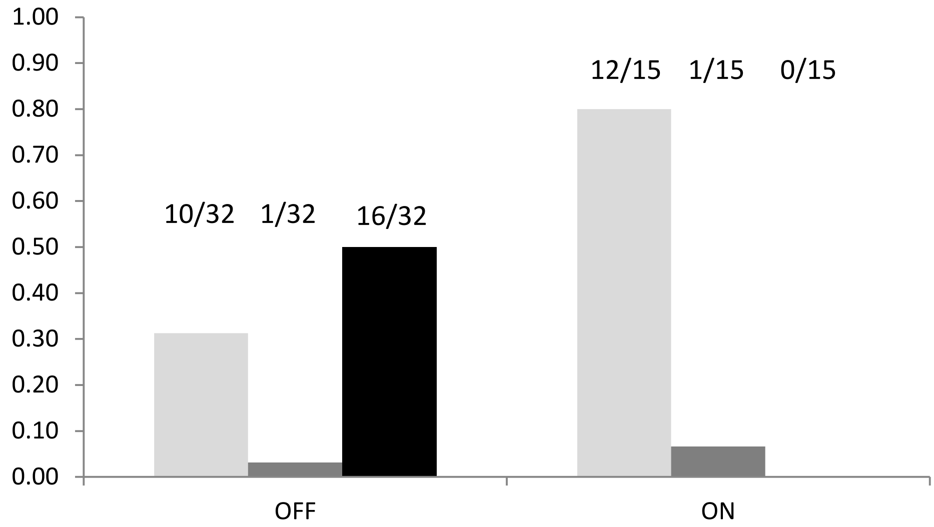

Figure 16. Proportion of investigations (light grey), aborted breaches (dark grey), and breaches (black) per assessable interaction compared when the deterrent was turned off or on. Numbers above bars indicate the number of event per replicate.

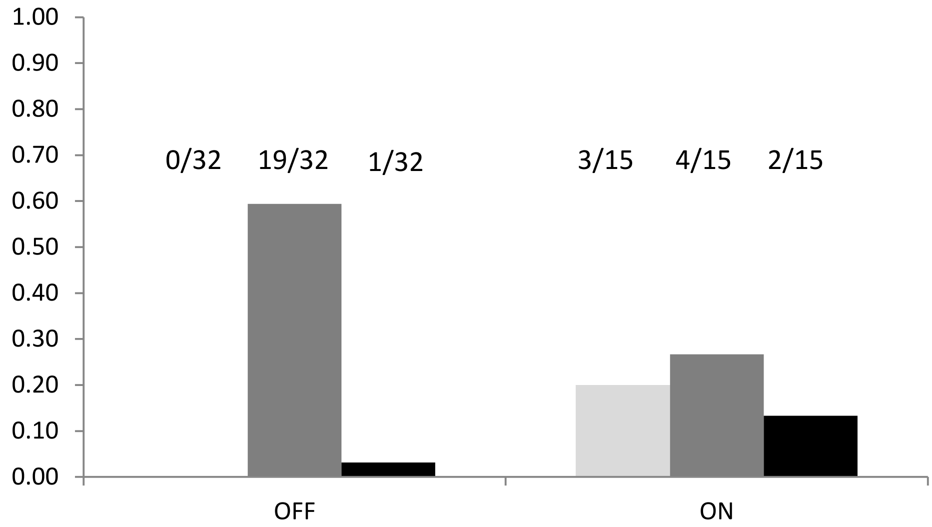

Figure 17. Proportion of sudden changes of direction (light grey), no change of direction (dark grey), and 'unsure' (black) per assessable interaction compared when the deterrent was turned off or on. Numbers above bars indicate the number of event per replicate.

5. DISCUSSION

This study is the first scientific assessment of the effects of the Shark Shield Freedom7™ on the behaviour of white sharks. The deterrent increased the time it took to take a static bait and the number of interactions per approach. On average, sharks did not approach as close when the deterrent was activated. There were some individual sharks that exhibited behaviours different to the mean trend; one shark took the bait four times faster when the deterrent was activated. Tows of a seal decoy showed that the deterrent reduced the number of breaches, surface interactions, and total number of interactions. The deterrent did not, however, affect the proportion of static baits consumed, nor did it reduce the number of underwater interactions with a dynamic bait. Sharks were also observed in some trials and tows within less than 0.5 m from the deterrent. The results showed that the deterrent had an effect on white shark behaviour, but did not deter or repel them in all situations, and for all individual sharks.

While this study is the first to test the effects of the Shark Shield Freedom7™ on white sharks, a previous study tested the efficiency of a previous model, the SharkPOD™, and found a 80% reduction in the probability of white shark taking a bait (Smit and Peddemors, 2003). This contrasted with the results from this study which did not find any differences in the proportion of baits consumed, regardless of whether the deterrent was activated. The disparity between these results might be due the position of the electrodes differing between the two models and potentially producing a geometrically different electrical field. Both models, however, have the same electronic circuit and produce the same pulse and waveform (Shark Shield Pty Ltd, pers. comm.). The position of the bait in relation to the deterrent was also different between the two studies. Smit and Peddemors (2003) attached the bait to the deterrent, whereas this study placed the deterrent 150–200 cm away from the bait, similarly to how a diver would wear the deterrent. This disparity in the experimental set-up potentially resulted in the discrepancy of the results obtained. Considering that the distance from the deterrent could have such large influence on its effectiveness in reducing the probability of an interaction, further testing should assess the impact that distance between the deterrent and a bait has on the probability of the bait being consumed.

While sharks were still capable of taking baits 150–200 cm away from the deterrent, the number of interactions within two metres of the deterrent decreased when it was activated. The mean minimum distance to the deterrent in this study of about 2.5 m was similar to that seen by Smit and Peddemors (2003). Using the same electronic deterrent as in this study, Galapagos sharks (*Carcharhinus galapagensis*) did not approach a bait canister two metres from the deterrent (Robbins and Peddemors, unpublished data). Sharks are, however, capable of being close to an activated deterrent, with the minimum distance recorded in this study being <0.5 m (Supplementary electronic information K, L). Sardines placed two metres away from an activated deterrent could also be taken by Galapagos sharks (Robbins and Peddemors, unpublished data). These studies indicate that electric deterrents can have an effect on sharks, but that sharks can approach and consume baits closer than 5 m to an activated deterrent.

During this study, white sharks took, on average, twice as long (120 seconds) to take the bait when the deterrent was activated compared to when it was switched off. An increase in the time it takes to consume a bait is consistent with findings for Galapagos sharks (Robbins and Peddemors, unpublished data). The number of interactions per approach also increased when the deterrent was activated, similar to the previous study on white sharks (Smit and Peddemors, 2003). This suggests that some white sharks may hesitate when taking a bait when a deterrent is activated

Based on the time taken by sharks to make their first approach towards the static bait and on the acoustically-derived presence/absence data, the deterrent did not attract sharks to the bait. The lack of difference in the first approach time, and in the number of detections prior, during, and after the experiments might be confounded by individual-specific variations, and care should be taken when interpreting these results. Indeed, while some sharks were detected more often when the deterrent was being tested, others were detected more often on days following the experiments. Based on the VRAP data, the location estimates during periods when the deterrent was not activated were differently distributed to periods when trials were not being undertaken. Sharks were closer to the vessel when trials were not undertaken than when trials were undertaken with the deterrent turned off. A bait was in the water during both periods, either as part of the experimental gear or to maintain sharks interest as part of cage-diving operations, and it is unknown why this difference was observed. This suggests that the VRAP system might not have been capable of adequately describing the behaviour of white sharks at large spatial scales (up to 200 m away) due to small sample sizes because the system did not record data during Trips 1 and 2. While small sample sizes precluded statistical analysis from being undertaken for individual sharks, the results from our study suggest that an activated deterrent does not attract white sharks to a static bait.

Experiments in South Australia may be biased by the berley and bait used to attract white sharks, and these may have modified the behaviour of the sharks on which the deterrent was tested. However, the rarity and cryptic nature of this species necessitates use of berley to investigate the effects of deterrents on a static bait, as it is essential to attract white sharks into the proximity of the deterrent to be able to observe their behavioural response and obtain sufficient replicates to allow robust statistical analyses. The difference in stimulation provided by a tuna bait, a different type of bait, an object, or a human was not measured. The deterrent, however, is intended to repel sharks and decrease the risk of shark attacks. If a shark attempts to attack an object, it is because the shark is interested in the object and motivated to attack it. As such, it was justified to test the effects of the deterrent on white sharks attracted to the research vessel such as through the use of berley and bait.

The field experiments took place in areas of high white shark concentration to ensure sufficient replication and sample sizes. Such aggregation areas are often where white shark cage-diving tourism has developed. For example, white shark cage-diving was initiated at the Neptune Islands in the 1970s and has been undertaken regularly since 2000. Wildlife tourism targeting sharks has previously been documented to impact the behaviour of some shark species (Bruce et al., 2005; Laroche et al., 2007; Semeniuk et al., 2007; Meyer et al., 2009; Clua et al., 2010; Smith et al., 2010; Barker et al., 2011b; Barker et al., 2011a; Bruce and Bradford, 2011; Fitzpatrick et al., 2011; Maljković and Côté, 2011). The behavioural response of white sharks to the deterrent might have also been modified by the impact of the cage-diving industry. Some white sharks are known to be 'temporary resident' at the Neptune Islands with regular visitations lasting up to 92 days (Bruce and Bradford, 2011). Some individuals involved in the static bait experiments might have been interacting with the cage-diving operators in previous years or during days prior to the trials. The white sharks that had previously interacted with the cage-diving vessels could also be considered as being accustomed to the disturbances associated with cage-diving operations. An additional disturbance in the form of a deterrent might not have the same impact as it would have in another location where white sharks are not as accustomed to human presence and disturbances. Sharks may have also been previously conditioned to taking baits leading to positive reinforcement. To reduce this potential bias, a future study should be conducted at locations where shark abundance is adequate to run trials, and where cage-diving does not occur.

Throughout the trials, sharks may have also become used to the effect and pulses of the deterrent, resulting in the potential for habituation in response to the pulse, or conditioning in response to the positive rewards obtained when baits were taken. For example, a shark which took the bait on the first trial when the deterrent was not activated, may be more likely to take the bait during subsequent trials. A shark that took a bait when the deterrent was activated may also be more likely to take a subsequent bait, as the discomfort caused by the deterrent may not have been strong enough to counter the food reward. Such temporal correlation has been observed in Galapagos shark interactions with a berley canister, where interactions declined following continued failures to obtain a food reward (Robbins and Peddemors, unpublished data). Sharks demonstrate cognitive ability (Clark, 1959; Aronson et al., 1967) and form associative learning behaviours as rapidly as other vertebrates (Guttridge et al., 2009), including following repeated exposure to electropositive metal deterrents (Brill et al., 2009). This potential bias was examined but there was no decrease with time in the number of approaches per trial, interactions per approach, minimal distance to the deterrent, time to first appear or time to take the bait. It is likely that the small number of food rewards provided and the alternation of positive and negative reinforcements from the deterrent being randomly activated for each trial prevented habituation from occurring and inducing any temporal effects in the study. The proportion of unidentified sharks (30.6%)

may have impacted our ability to detect a decreasing response of individual sharks to the pulses emitted by the deterrent. The issue of habituation or conditioning might have also occurred with the towed seal decoy. However, given the low number of interactions recorded when the deterrent was activated, the likelihood of habituation is low.

Experiments in South Africa showed that all 16 breaches observed during the 190 tows undertaken occurred when the deterrent was turned off. Considering the 0.16 probability of breaching occurring (based on the 16 breaches obtained in the control situation), the probability of having less than one breach during the 91 tows undertaken with the activated deterrent is <0.001 (based on a binomial distribution). Similarly, while a total of 27 surface interactions were observed, only two occurred when the deterrent was activated. Using a similar principle, the probability of having two or less surface interactions during the 91 tows when the deterrent was activated is also <0.001. It is therefore unlikely that the lack of breaches and small number of surface interactions observed when the deterrent was turned on was due to chance.

Considering that the number of breaches and surface interactions decreased when the deterrent was activated, it might be expected that the number of underwater interactions would increase as sharks abort their predatory behaviour. There was, however, no significant difference in the number of underwater interactions, whether or not the deterrent was activated. The expected increased number of aborted breaches may have been counterbalanced by a similar decrease in the number of approaches by white sharks, leading to the same number of underwater interactions occurring regardless of the deterrent's operational status. This is further supported by the underwater behaviour, which indicated a decreased proportion of breaches, but an increased proportion of aborted breaches and investigations when the deterrent was activated. In addition, interactions when a reaction was observed were only recorded when the deterrent was activated, while interactions when sharks did not react decreased.

If the deterrent caused the observed decrease in the frequency of breaches, a proportional increase of aborted breaches would have been expected. Similarly, it would have also been expected to record a reaction from sharks in close vicinity of the activated deterrent. This was not the case, and only 6.7% of the interactions were aborted breaches, while a reaction was only observed in 20% of the interactions. This could be explained by: (1) the differences in the number of breaches, surface interactions, and behaviour type is not due to the deterrent but to another factor that was unaccounted for; (2) the behaviours of the sharks could not be reliably coded; or (3) some white sharks affected by the deterrent were not detected by the underwater filming due to being outside the visibility range of the camera. On most days, the visibility was estimated to be 3–5 m or less. As such, if sharks were affected by the deterrent from further than the visibility range of the camera, they would have to be affected by the deterrent further away than 3–5 m. This contradicts the results obtained from the static bait experiments, which suggests that the deterrent did not affect white sharks further than a distance of two metres. While the deterrent can affect sharks to a distance of up to two metres, white sharks could also be able to detect the pulse of the deterrent from further away and react to it from a distance not observable by the underwater camera. If white sharks are capable of detecting the electric pulse emitted by the deterrent prior to initiating a predatory attack, they might decide not to initiate a breaching approach, which would explain the small number of aborted breaches observed. The minimum detection threshold and voltage strength that elicits a behavioural response has been measured for several shark species (Marcotte and Lowe, 2008; Jordan et al., 2011). An accurate mapping of the electric field emitted by the deterrent would enable quantification of the expected distance from which sharks first detect the field and the distance from which sharks could be expected to respond behaviourally.

The trials using the towed seal decoy off South Africa suggested that the deterrent affected the predatory behaviour of white sharks. Although the deterrent appeared to impact the predatory behaviour of white sharks, several individuals were observed in close proximity to the deterrent, some touched the electrode (Supplementary electronic information M), and two surface interactions were observed when the deterrent was activated. The deterrent emits an electric pulse every about 0.6 seconds (Shark Shield Pty Ltd, pers. comm.). White sharks have been estimated to breach at speeds of 35 km/hr (or 9.7 m/s) (Martin and Hammerschlag, 2012) and lamnid sharks have been estimated to be capable of burst speeds of up to 56 km/hr (15.6 $m.s^{-1}$) (e.g., *Isurus oxyrinchus* (De Maddalena et al., 2005)). A white shark could, therefore, theoretically travel at least 5.82 m and up to 9.3 m during the time between the two pulses emitted by the deterrent. Therefore, a white shark undertaking a predatory targeted strike or at full speed could reach the centre of the electric field emitted by the deterrent during the 0.6 second interval between the two pulses. In addition to white sharks being observed in close proximity (<0.5 m) to the activated deterrent, they could also theoretically reach the deterrent between two pulses.

The main findings of the static and dynamic experiments were different. The operational state of the deterrent did not affect the proportion of static baits taken, but an activated deterrent did significantly decrease the number of breaches and surface interactions on a towed seal decoy. While the differences observed could be due to location or the different white shark populations (Gubili et al., 2012), it is more likely related to the behavioural states being tested. White sharks that investigate a static bait are mostly swimming at slower speeds than when hunting natural prey. It is likely that the energy required for a breach is higher than that expended during inquisitive behaviour. Considering the energetic cost of breaching, white sharks might be less likely to breach if they can sense any factor that could reduce their chance of being successful or which seems unusual. In the presence of a deterrent, a white shark might still be inquisitive around a static bait where energetic cost is similar to normal swimming, but they might be less likely to breach because of the higher energetic cost. The investigatory nature of the inquisitive behaviour is supported by the number of times the same white sharks were observed (e.g., one white shark approached the static bait in 35 different trials, while another individual had 18 interactions in one trial).

While we tested the response to the deterrent in two interaction types, it cannot be assumed that white sharks would respond similarly when interacting with humans or other visual or chemical stimuli, such as from a marine mammal carcass or other potential prey items. The results obtained also cannot be extrapolated to different types of predatory behaviour (e.g. non-breaching surface predation, subsurface predation) as different behavioural responses may occur in response to the deterrent.

6. CONCLUSIONS

This study suggests that white shark behaviour is environmentally and contextually specific, and that the degree of risk reduction afforded by use of the electric deterrent we tested is likely to depend on the behavioural state of sharks. The deterrent we tested had an effect on white shark behaviour, but did not deter or repel them in all situations nor did it repel all individual sharks. While it was expected that the deterrent would dissuade white sharks from taking a static bait (Smit and Peddemors, 2003), the ability of the deterrent to stop a white shark in a targeted predatory behaviour was unknown.

Results suggest that the incidence of predatory strike may be reduced by an activated deterrent and that the deterrent affected the behaviour of white sharks at up to two metres from the source of the field. It is not known whether the effective distance of the deterrent varies between species, which warrants further investigation to better define performance guidelines. Given that the static bait experiments showed that an activated deterrent did not reduce the likelihood of baits being taken, the risk reduction observed in the seal decoy study would not be provided in all situations. Although the data were limited, our results suggest that white sharks were not attracted to the deterrent.

7. FUTURE RESEARCH

Future studies should focus on testing the effects of the deterrent at different distances, to assess if a deterrent closer than two metres to the attractant can prevent white sharks from taking a bait. An accurate map of the electric field emitted by the deterrent would also aid in determining the distance from which sharks can be expected to first detect and react to the deterrent. Similar tests to those undertaken during this study should be conducted at other locations where regular berleying and cage-diving does not occur. A different site would facilitate testing of the deterrent without the potential biases of habituation to human disturbance, berley, and use of the tuna teaser baits that are used at cage-diving sites. Finally, the study was undertaken on white sharks and should also include other sharks that have been implicated in attacks on humans, such as tiger sharks (*Galeocerdo cuvier*), and bull sharks (*Carcharhinus leucas*).

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