Response of white sharks exposed to newly developed personal shark deterrents

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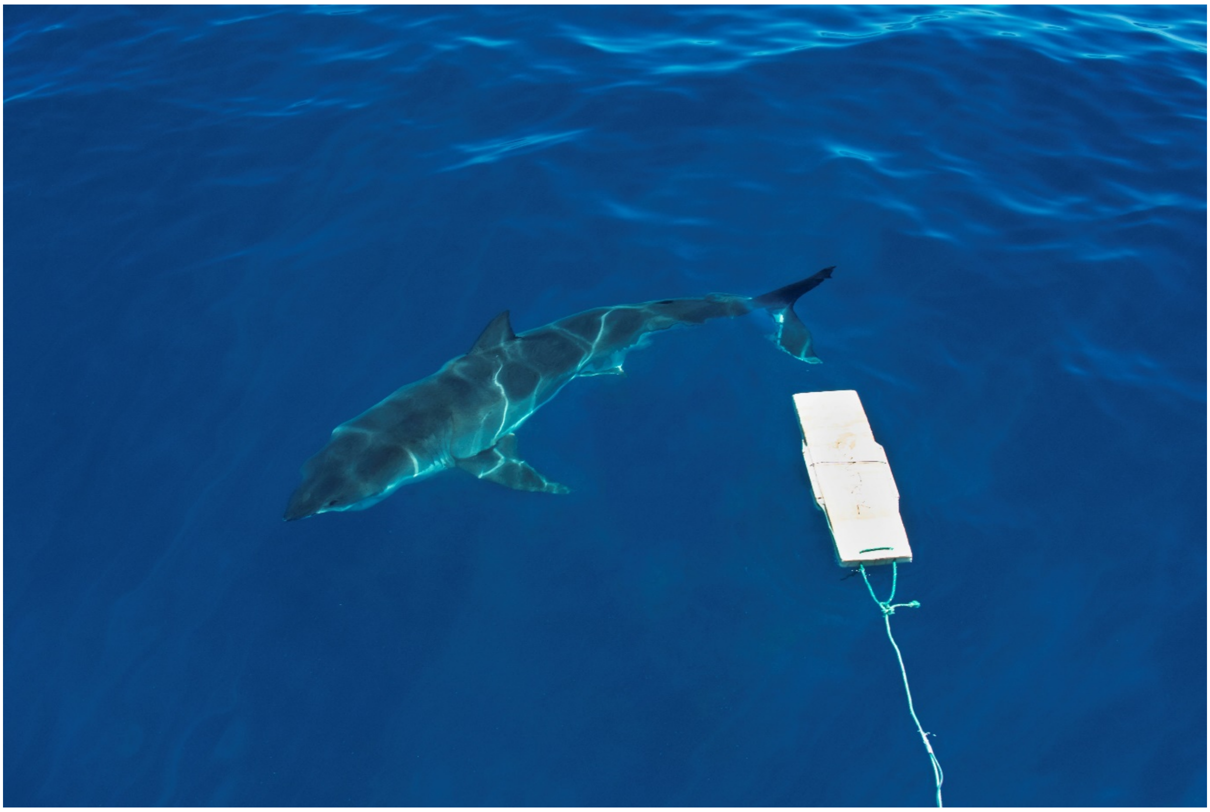

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4. ACKNOWLEDGEMENTS

This project was done under the Department of Environment, Water and Natural Resources permit M26609 and Flinders University ethics approval E446. This project was funded by the New South Wales Department of Primary Industries Shark Management Strategy (SMS) Competitive Annual Grants Program, Government of South Australia, Ocean Guardian Pty Ltd, and the Neiser Foundation. We openly and transparently declare that Ocean Guardian contributed financially to the study, but that Ocean Guardian was not involved in the study design or implementation, nor did they have access to the data post-collection. Nor did Ocean Guardian provide input into data analysis, interpretation, writing of the report, or the conclusions drawn. The study design followed a protocol developed for a previous study (Huveneers et al. 2013b), which was not funded by Ocean Guardian. In summary, Ocean Guardian had no opportunity to influence any aspect of the study or its conclusions, apart from providing some financial support to realise the field project (e.g., boat hire, equipment purchase, etc.) in the same manner as the other funding agencies. The South Australian cage-diving industry provided logistical support during the testing of the deterrents. The authors thank Jens Neiser, volunteers, and staff from Rodney Fox Shark Expeditions for their help during testing of the deterrents, and René Campbell for illustrating the board set-up (Figure 1).

5. EXECUTIVE SUMMARY

- In Australia, the number of shark-human interactions and shark bites per *capita* has increased, leading to a rise in shark-bite mitigation measures being developed. Yet, many of the products commercially available have not been scientifically tested, potentially providing an exaggerated sense of security to members of the public using them.
- We tested five shark deterrents developed for surfers (*Shark Shield Pty Ltd* [*Ocean Guardian*] *Freedom+ Surf, Rpela, SharkBanz bracelet, SharkBanz surf leash* [*Modom*]*,* and *Chillax Wax*) by comparing the percentage of baits taken, time to take the bait, number of passes, distance to the bait, and whether a shark reaction could be observed.
- A total of 297 successful trials were done at the Neptune Islands Group Marine Park. During these trials, 44 different white sharks (*Carcharodon carcharias*) interacted with the bait, making a total of 1413 passes.
- The effectiveness of the deterrents was variable, with the *Freedom+ Surf* affecting shark behaviour the most (increased number of reactions) and reducing the percentage of bait taken from 96% (relative to the control board) to 40%. This led to an increase in the number of passes because exposed sharks continued to attempt taking the bait. Shark's mean distance to the board increased from 1.6 ± 0.1 m (control board) to 2.6 ± 0.1 m when the *Freedom Surf+* was active, but the time it took to interact with the bait remained indistinguishable. The other deterrents had limited or no measureable effect on white sharks.
- Based on our power analyses, the smallest effect size that could be reliably detected was ~ 15%. Although we did not find evidence that the *magnet band* and *leash*, *Chillax Wax*, and *Rpela* affected white sharks during the trials, it is possible that these deterrents have small effects that could not be detected by the 50 trials per deterrent we imposed. This does not infer that additional trials would have necessarily resulted in our models detecting an effects from these deterrents; rather it means that more than 50 trials would be required to detect changes of a magnitude < 15% greater than we observed if there were any effects.
- Manufacturers should consider these findings to assess the suitability of their product and gauge whether changes are required to ensure that their product performs as intended. Our results will allow private and government agencies to make informed decisions about the use of these devices for occupational activities and enable the public to make appropriate decisions about the use and suitability of these five products.

6. INTRODUCTION

Although shark-human interactions remain rare and unlikely events, their frequency has been increasing globally (Chapman and McPhee 2016, McPhee 2014). Growth in human population, habitat modification and destruction, water quality, climate change and anomalous weather patterns, and the distribution and abundance of prey have all been proposed to explain this recent increase in the incidence of shark bites and shark bites per *capita* (Afonso et al. 2017, Chapman and McPhee 2016, Lemahieu et al. 2017, McPhee 2012, Meyer et al. 2018). However, the infrequent occurrence of such events impedes our ability to assess the relative importance of causal factors that might have contributed to the rise in the global and regional number of shark bites (but see Afonso et al. 2017 and Meyer et al. 2018). While the probability of being bitten by a shark is low, and most shark bites result in minor injuries (West 2011, Woolgar et al. 2001), public perception of the risk of shark bites and ensuing fatality is much higher than reality (Crossley et al. 2014, Myrick and Evans 2014). The frequent negative framing by the mass media, social media, and user-driven content sites (e.g., YouTube) might have contributed to exaggerating public anxiety about the pervasive presence of sharks and risk that they pose to humans (Muter et al. 2013, Sabatier and Huveneers 2018). Such heightened public concern has pressured managers and governments to develop and implement new measures that reduce the risk of sharks bites, and provide information to the public to make more informed decisions about using a specific area at a particular time.

Prevention and responses to shark bites have varied temporally and regionally, and have included shark hunts, organised shark culling, 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 sharks and humans encountering each other, other measures aim to repel sharks directly from approaching people in the water. These deterrents have been developed to elicit a response by impacting one or more of the shark senses, including vision, smell, and electro-reception (Table 1; and see Hart and Collin 2015). For example, various aposematic colour configurations (i.e., use of colours as anti-predator tactics) have been proposed allegedly to repel sharks. Using chemicals as shark repellents has also been proposed (Baldridge 1990, Rasmussen and Schmidt 1992, Sisneros and Nelson 2001). However, the sensitivity of the electro-receptive organ of sharks to strong electric fields and its potential ability to deter sharks have been studied the most (e.g., Huveneers et al. 2013b, O'Connell et al. 2014b).

The rise in shark-human interactions has also led to the emergence of many new personal shark deterrents. The rapid commercial availability of these deterrents has preceded rigorous and peer-reviewed studies to test the effectiveness of these devices, meaning that manufacturers are making claims about their products without rigorous scientific evidence to back them up. If deterrents were not as effective as advertised, it could give users a false sense of security, leading some people to put themselves at greater risk of shark interactions than they normally would because of the reliance of these devices. For example, some surfers and spearfishers ignore other mitigation measures, such as beach closures, because they feel safe when wearing these products. Whether they are or not is what we aim to demonstrate in this study.

Surfing has been suggested as an activity that exposes people to sharks more than others, because many ideal surfing locations are regions that overlap with the habitats of potentially dangerous sharks, the amount of time surfers spend in the water relative to most other bathers, surfers' distance from shore, isolation, possible resemblance to white sharks' natural prey (i.e., seals, fur seals, and sea lions), and potentially enticing arm and leg movements (Burgess et al. 2010). For example, most bites in Volusia County, USA (63%) between 1982 and 2013 occurred during surfing activities, while surfing has also been implicated in 53% of shark bites in Brazil since 1992 (Chapman and McPhee 2016) and two-thirds of shark bites in Reunion Island (McPhee 2014). This has resulted in recent development of personal deterrents to decrease the risk of shark bites to surfers.

Our aims were to test the effectiveness of surfing-specific personal shark deterrents and quantify the behavioural response of sharks exposed to these deterrents. We tested the effects of five deterrents (two electric, two magnetic, and one olfactory-based) on the behaviour of white sharks (*Carcharodon carcharias*) and determined if these deterrents reduce the likelihood of white sharks consuming an intended prey. Specifically, we assessed and compared the effects of each deterrent on (1) the number of passes to a bait, (2) the minimum distance between a bait and the sharks, (3) the percentage of bait taken, (4) the amount of time sharks took to take the bait, and (5) whether shark behaviour changed with increased exposure to the deterrent. We also assessed the effect size that the trials could detect statistically (power analysis) to gauge the experiment's ability to identify small behavioural changes if present.

Table 1. Examples of shark deterrents commercially available and their cost (as of 19 April 2018).

Deterrent type	Company	Product	Webpage	Cost (AU$)
vision-based	Sharkproof	*Mask Strap*	www.sharks-diving.com/Buy-now	25
	Shark Attack Mitigation Systems	*SAMS 5' Vinyl Shortboard Sticker*	shop.sharkmitigation.com/board-stickers-and-inlays/short-board-stickers/sams-5-vinyl-shortboard-sticker.html	104
	Radiator	*Shark Deterrent Surf*	radiator.net/collections/shark-deterrent-surf-range	495
		Shark Deterrent Dive	radiator.net/collections/shark-deterrent-dive-1	528
	Shark Shocker	*Beware*	thesharkshocker.com	96
acoustic-based	Shark Stopper	*Watercraft Shark Repellent*	www.sharkstopper.com	unknown
olfactory-based	CommonSense Surf Company	*Chillax Wax*	www.facebook.com/commonsensesurf	18-20
	SharkTec	*Instant Release Repellent Spray*	www.sharktecdefense.com/products/instant-release-shark-repellent-spray	50
	RepelSharks	*Shark Deterrent Canister*	repelsharks.com/repel-sharks-shark-deterrent-canister-2	38
	Best Glide	*BCB Shark Repellent*	www.bestglide.com/shark_repellent.html	34
electroreception-based	Shark Shield (Ocean Guardian)	*Freedom+ Surf*	sharkshield.com/shop/freedom-surf-bundle	599
		Scuba 7	sharkshield.com/shop/scuba7	799
		Freedom7	sharkshield.com/shop/freedom7	749
	Rpela	*Rpela*	www.*Rpela*.com/products	340
	SharkBanz	*SharkBanz 2*	www.sharkbanz.com/products/sharkbanz-2	90
		Shark Leash	www.sharkbanz.com/products/modom-shark-leash	167
	Shark Shocker	*Lucky Leash*	thesharkshocker.com	50
		Shark Shocker	thesharkshocker.com	42
	Bluvand	*NoShark – dive version*	bluvand.com/shop/bluvand/noshark-dive-version	514

7. METHODS

7.1 Study species and site

In Australia, the white shark is responsible for the most unprovoked bites (19.5% of all shark bites) and the most fatalities (34%) (West 2011). Our study focused on white sharks because interactions with this species are considered to be a worst-case scenario during which the deterrent is subjected to the most dangerous species. We did all deterrent testing trials at the Neptune Islands Group Marine Park (35°149 S, 136°049 E). This group of islands is ~ 30 km off the southern coast of South Australia, supports the largest colony of fur seals in Australia (Goldsworthy et al. 2014, Shaughnessy et al. 2005), and is considered an aggregation site for white sharks (Huveneers and Lloyd 2017). Commercial shark-cage diving has taken place here since the late 1970s and is the only location where such activity is permitted in Australia (Huveneers et al. 2017).We chose this area because the high likelihood of shark interactions. We did the deterrent testing over 18 days and five separate trips between September 2017 and January 2018.

7.2 Deterrent set-up

We tested five commercially available deterrents (*Shark Shield Pty Ltd* [*Ocean Guardian*] *Freedom+ Surf, Rpela, SharkBanz bracelet, SharkBanz surf leash* [*Modom*]*,* and *Chillax Wax*; Table 2) using custom-built surfboard replicas (hereafter referred to as 'boards'). In the case of the *Rpela*, we did the trials first using the commercially available device. We made minor modifications to the electrode size through the trials, but this did not affect shark responses (see results). Boards were 120 × 30 cm and made of polystyrene foam covered with layers of fibreglass cloth and epoxy resin, but were strengthened with wood on the sides where the bait was attached. We used six boards, with each having one active deterrent and four replica or dummy deterrents to act as a control (Fig. 1). One board had no active deterrents (i.e., it had the five dummy deterrents) and was used as the control. For example, the *Shark Shield* (*Ocean Guardian*) *Freedom+ Surf* (hereafter referred to as *Surf+*) board consisted of an active *Surf+*, regular wax, a replica *Rpela*, and a dummy *SharkBanz bracelet* and *leash*. This experimental set-up allowed us to test for each active deterrent type using a single control board.

Table 2. Five commercially available deterrents tested with their recommended use and the dummy deterrent used in our study.

Deterrent type	Brand/product	Recommended attachment type	Dummy deterrent
olfactory	*Chillax Wax*	Wax applied to the top of surfboard	Regular surfboard wax
magnetic	*SharkBanz - bracelet*	Worn on ankle or wrist of surfer	Non-magnetised black plastic bracelets
magnetic	*SharkBanz - leash*	Incorporated within surfboard leash	Non-magnetised regular leashes
electric	*Ocean Guardian Freedom+ Surf*	Electrode stickers placed on bottom of surfboard, electronics incorporated within tail kick of back grip	Replica electrodes created using silver permanent marker and white tape
electric	*Rpela*	Electrode and electronics built-in on bottom of surfboard	Replica *Rpela* unit without active device

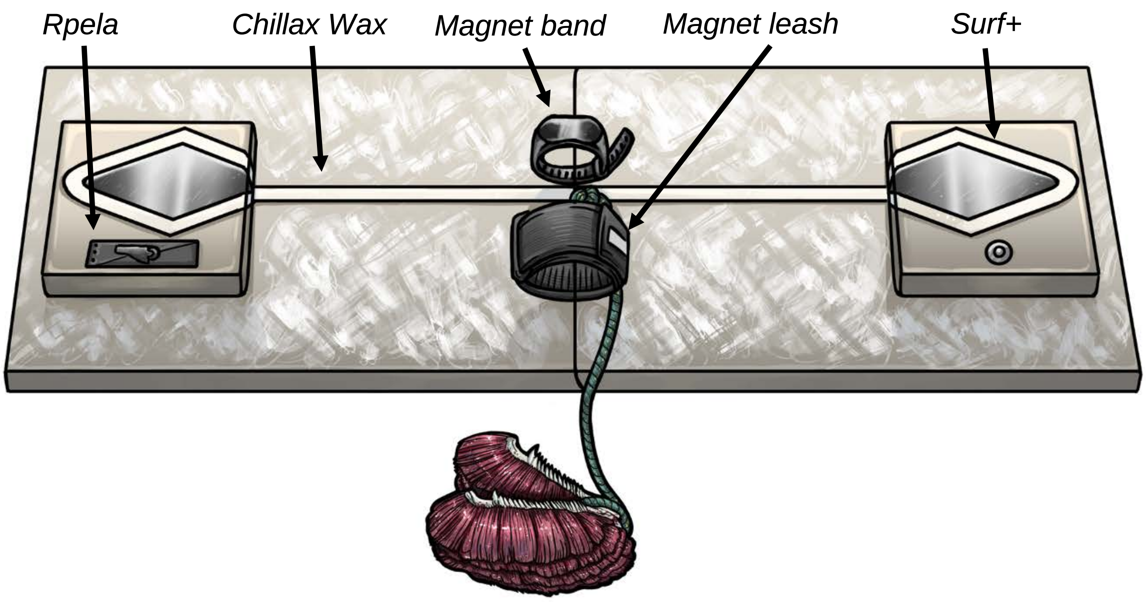

Figure 1. Illustration of the board set-up with the five deterrents tested (illustration by René Campbell, Flinders University).

7.3 Field sampling

Across the five sampling trips, we tested each deterrent a total of 50 times within a series of trials. A series of trials consisted of testing each of the five deterrents and the control board (total six trials) in a randomised sequence. This led to a total of 300 trials (50 trials for each of the five deterrents and control).

White sharks were attracted to the stern of an anchored vessel using an odour corridor, which we established by disbursing into the water a mix of unrefined fish oil and minced southern bluefin tuna *Thunnus maccoyii*. We attached sections of tuna with short lengths of natural fibre to a float secured by a 15 m line. We allowed the tuna section to drift from the stern of the vessel to attract white sharks. 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. We removed and replaced the tethered bait with the experimental equipment, which we only deployed when the shark had left the proximity of the vessel and was no longer visible. Each trial consisted of the deployment of a fresh tuna gill (~ 2 kg), referred to as the 'bait', which we attached ~ 30 cm beneath the board to replicate the typical distance between a surfer's foot and the board when surfers sit on their board to wait for a wave. We connected the board to the stern of the anchored vessel using a rope, and left it to drift with the wind and tide. The distance of the equipment from the vessel varied between 5 and 15 m depending on the wind, swell, tide, and glare conditions, to ensure that observers on the vessel could identify sharks and record their behaviour accurately. We ran trials for 15 minutes or until a shark touched the bait or board with an intent to consume the bait. We repeated trials during which a shark did not approach the board with an intent to take the bait to ensure that the results were not biases by trials during which sharks did not attempt to consume the bait.

During each trial, we deployed a stereo-video unit from the stern of the boat ~ 50 cm below the surface to film and enable coding of each trial. The stereo-video unit consisted of two GoPro Hero4 Silver edition cameras mounted in secure custom-built housings (SeaGIS Pty Ltd, Victoria, Australia) angled 8 degrees inward and set 76 cm distance apart along a metal bar. We calibrated the cameras using an EventMeasure Stereo to take accurate length measurements from the video footage. This software uses the 3-dimensional calibration information to calculate distance.

7.4 Video processing and filtering

We processed and analysed the video footage using EventMeasure. We reviewed and independently coded the digitally recorded video footage from each trial. The coders were 'blind' because they did not participate in all of the trials and had no prior knowledge of which deterrent was being used when coding videos of each trial. We used the following terminology to describe and code shark behaviour following Huveneers et al. (2013b):

- *Pass*: a directed swim towards the experimental set-up (each time a shark veered away from the board and swam back we classified it as a new pass);

- Shark identity: We individual white sharks based on markings on five morphological areas: caudal fin, pelvic fins, first dorsal fin (hereafter dorsal fin), gills, and pectoral fins using established white shark identification methods (Nasby-Lucas and Domeier 2012, Nazimi et al. 2018). We could recognise most individuals through a combination of pigmentation patterns (countershading, rosettes, islets, freckles, spots), notches or scoops, amputations, scoliosis, and scars. As natural pigmentation patterns can gradually change in some individuals (Domeier and Nasby-Lucas 2007, Robbins and Fox 2013), using multiple morphological areas to identify and resight individuals reduces the likelihood of misidentifications (Gubili et al. 2009, Towner et al. 2013). We applied side by side comparisons of fin silhouettes (dorsal, caudal, or pectoral) and videos of sharks turning and showing both sides to link left- and right-hand sides of shark images;
- Distance to bait: distance from the sharks' nose, where the shark's sensory organs targeted by the deterrents (ampullae of Lorenzini, nostrils) are located, to the top of the bait;
- Level of intent: this represented the shark's motivation when approaching the bait; we categorised this as *high, medium*, or *low* using a combination of factors including shark swimming direction in relation to the bait, swimming speed, and acceleration amount. *low* = shark moving slowly, not approaching in the direction of the bait and without acceleration; *medium* = shark slowly moving towards the bait without acceleration; *high* = shark approaching the bait at speed or accelerating;
- Approach type: we categorised the position of the shark in the water column when approaching the bait as either *surface* (horizontal swimming near the surface), *deep* (horizontal swimming 2 m), or *vertical* (shark comes up from below the bait and swims vertically in a typical breach approach);
- Reaction: a behavioural reaction from an individual shark towards the experimental set-up (e.g., tail flick, muscle spasm, head shake, fast direction change).

We determined sex based on clasper presence and measured total body length using EventMeasure. We did not include the effect of shark sex or size in the analysis because potential differences here were beyond the scope of our study. Instead, we included individual shark (shark ID) as a random effect in the models (see below) to account statistically for individual shark behaviour that was independent of deterrent effects (i.e., some sharks might be more included to approach closer or more frequently than others). Prior to analysis, we removed passes that had low intent or that were deep and not directed at the board to avoid including behaviours where sharks were not attempting to consume the bait.

7.5 Data analysis

There were two potential analytical biases in the data we collected: (1) temporal correlation (lack of temporal independence) due to the potential habituation of individual sharks or changes in their motivation through time, and (2) pseudo-replication due to instances where the same shark interacted with the bait within and across trials. Sharks might become habituated to the deterrent, or sharks that consumed the bait might become less likely to respond to the deterrent due to the positive reinforcement provided by the bait. We investigated whether the effectiveness of the deterrents changed throughout the study (e.g., sharks becoming habituated to the deterrents) by including 'trial' as a fixed integer covariate in the models (i.e., ignoring the real elapsed time between successive exposures but including the information indicating relative serial time; e.g., 2 followed 1) and by plotting the mean distance between the shark and the board, and the number of passes across trials for sharks that interacted with the board for 15 trials or more.

We minimised potential pseudo-replication by testing the effects of deterrents on all response variables using a generalised linear mixed-effects model (GLMM) with individual shark coded as a random effect, and the deterrent used as the fixed effect. We also included trial as fixed-integer effect and the interaction between trial and deterrent to account for potential temporal effects. 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. Including individual shark as a random effect accounted for the potential lack of independence in behaviour within each identified shark. We excluded those passes for which we could not identify the shark from this analysis (117 out of 1,413 passes; 8.2%). We determined the most appropriate statistical family and error distribution for each analysis by examining the distribution of the response variable and visually inspecting the residuals for the saturated models. We ran all models for all possible combinations of factors, and compared their relative probability using Akaike's information criterion corrected for small sample size (AIC_c) (Burnham and Anderson 2002). The bias-corrected relative weight of evidence for each model, given the data and the suite of candidate models considered, was the AIC_c weight; the smaller the weight, the lower its contribution to parameter estimates (Burnham and Anderson 2002). We also calculated the marginal R^2 of each resampled GLMM (R_m) as a measure of goodness of fit and the contribution of the fixed effects to explaining variance in the response variable (Nakagawa and Schielzeth 2013). We also compared the proportion of time the board or baits were touched or taken by sharks between deterrents using the minlike two-sided Poisson exact test from the *exactci* R package (Fay 2010). We used this test because it is generally more powerful than the central two-sided method (Fay 2010).

7.6 Power analysis

Using the variance structure of the observed datasets, we determined how much an increase in the response was required to give statistical evidence for an effect of each deterrent. We first separated each deterrent-control combination for each of three responses: proportion of bait taken, distance to bait, time to take bait, and number of passes. For each subset, we increased the response variable measured for the deterrent trials by 5% increments up to a maximum of 150% of the observed values (i.e., multiplying by a scalar of 1, 1.05, 1.10, …, 1.5). Within each incremented set, we randomly resampled the entire subset with replacement (i.e., all rows, including both control and treatment [deterrent type]) up to the same number of samples, repeating this procedure 1000 times. For each iteration, we recorded the information-theoretic evidence ratio of the model including only the deterrent fixed effect (i.e., model 3; response ~ deterrent + shark ID random effect) relative to the intercept-only model (i.e., $w\text{AIC}_c$ of model 3 ÷ $w\text{AIC}_c$ of the intercept-only model). We then plotted the median (and 95% confidence bounds) of model 3 evidence ratio against the response increment. We concluded that an effect could become statistically distinguishable from the control when the most common top-ranked model started to include a *deterrent* effect, and when the evidence ratio became >> 2 (i.e., the *deterrent* model was at least twice as likely to be the true model relative to the intercept-only [no effect]).

8. RESULTS

Across the five trips, we did a total of 342 trials, from which we removed 42 from further analysis because no sharks approached the board with an intent to take the bait during these trials. We also removed two trials with the *Surf*+ and one trial with the *Rpela* due to technological issues with the device at the time of deployment. Out of the remaining 297 trials, we recorded 1413 passes from a total of 44 individual sharks. The mean (± standard error) distance between sharks and baits was 2.30 ± 0.04 m (range: 0 – 10.8 m; *n* = 1217 passes), which we measured with a precision of 46.5 ± 1.0 mm (2.3 – 325.4 mm). Passes for which we could not measure distance (*n* = 196) were due to objects (e.g., bubbles from weather conditions, other fish species such as silver trevally) obstructing the field of view or to the framing of the video cutting off the board and bait or the shark. Individual sharks interacted with the board for an average of 29.5 ± 5.3 passes (range: 1 – 152) and 8.9 ± 1.4 trials (range: 1 – 41). The mean number of sharks that approached the bait during a trial was 1.3 ± 0.03 (range 1 – 4). Most (68%) passes occurred at the surface, with only a few (4%) vertical passes. Overall, the distribution of pass type was approximately evenly distributed among the intent classes: 38, 40, and 23% high, medium, and low intent, respectively. However, this distribution reversed between surface and deep passes because most surface passes had high intent and most deep passes had low intent (Fig. 2).

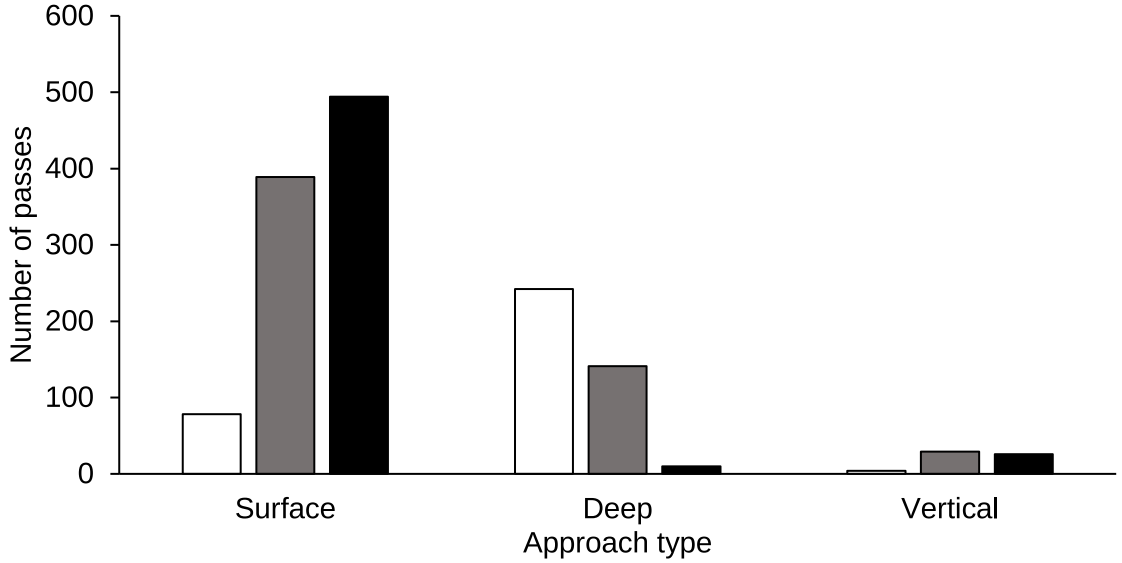

Figure 2. Number of passes of white sharks (*Carcharodon carcharias*) during the 297 trials according to approach type and level of intent (white = low; grey = medium; black = high).

When no deterrents were active (i.e., on the control board), sharks touched or bit the board or bait (hereafter referred to as an 'interaction') prior to the end of the trials 96% of the time. The deterrents had various effects, with the percentage of times sharks interacted with the bait ranging from 94% (*magnet leash*) to 40% (*Surf+*) (Fig. 3a). The *Surf+* was the only deterrent that had statistical evidence for reducing the percentage of times sharks interacted with the bait (Poisson exact test: $p < 0.001$; $p > 0.67$ for all other deterrents). The $w\mathrm{AIC}_c$ top-ranked model ($w\mathrm{AIC}_c = 0.73$) included deterrent, with the deterrent factor explaining ~ 23% of the variance (Table 3). The *Surf+* had the largest effect on the percentage of time sharks interacted with the bait (-4.9%) compared to the other deterrents (-0.3 to -1.9%) (Table 4).

We observed reactions 117 times at an average distance of 1.49 ± 0.05 m (range: 0 – 6.1 m) from the board and they occurred most frequently with the *Surf+* (68% of reactions). The *Surf+* was the only deterrent that demonstrated statistical evidence for changing the percentage of reaction (18%) compared to the control board (2%) (Poisson exact test: $p = 0.046$; $p > 0.49$ for all other deterrents) (Fig. 3b). When the *Surf+* was active, we observed reactions at an average distance of 1.72 ± 0.05 m (range: 0 – 6.1 m) from the board (Fig. 3c).

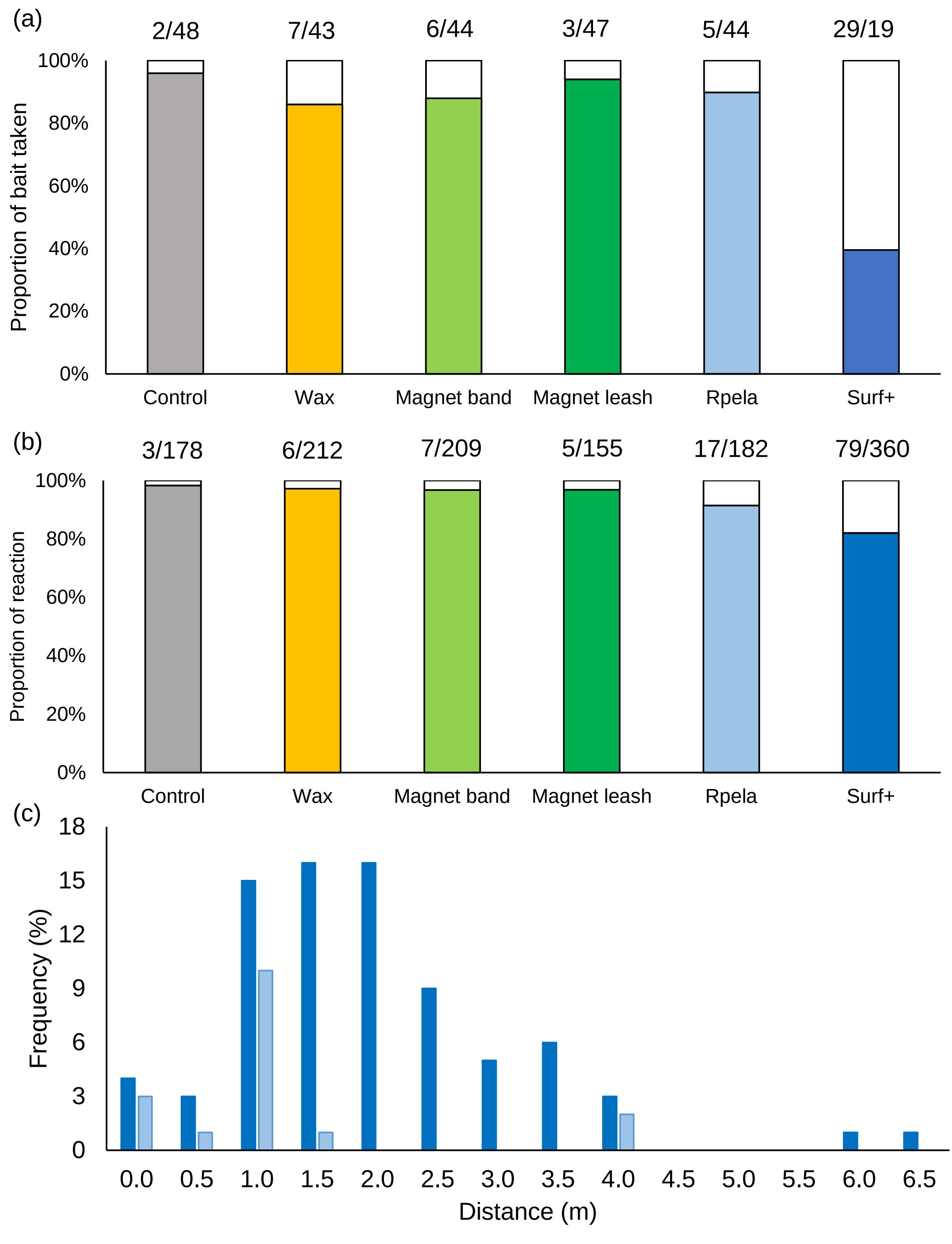

Figure 3. (a) Percentage of board or bait touched or taken and (b) reaction by white sharks during 15-minute trials with a control board (grey) or one of five deterrents (coloured bar). White bars represent trials when the board and bait were not touched or taken, or without any reaction. Numbers above bars represent (a) the number of trials with board and bait touched/taken or not touched/taken and (b) the number of pass with or without reaction. (c) Frequency distribution of the distance at which white sharks (*Carcharodon carcharias*) reacted to the *Rpela* (light blue; *n* = 17) and the *Shark Shield (Ocean Guardian) Freedom+ Surf* (dark blue; *n* = 79). Only deterrents for which sharks reacted more than 15 times were included.

Table 3. Summary of models estimating the effects of deterrents on the probability of the board or bait being touched or bitten by white sharks. k = number of model parameters; AIC_c = Akaike's information criterion corrected for small sample size; ΔAIC_c = difference in AIC_c between the current and the top-ranked model; $wAIC_c$ = model probability; R_m = marginal (fixed effects) R^2. All models include shark ID as a random effect and a binomial error distribution (logit link).

Model	**k**	**AIC_c**	**ΔAIC_c**	**$wAIC_c$**	**R_m**
bait ~ deterrent	7	178.97	0.00	0.73	23.1
bait ~ deterrent + trial	8	180.96	1.99	0.27	23.1
bait ~ 1 (intercept-only)	2	234.48	55.51	< 0.01	-
bait ~ trial	3	236.09	57.12	< 0.01	0.6

Table 4. Estimated deterrent level coefficients (β) and their standard errors (SE), z-values of factors included in the top-ranked model (bait ~ deterrent; Table 3), and the individual coefficient Type I error estimate (P).

Level	**β**	**SE**	**z**	**P**
intercept	3.061	1.013	3.02	0.003
Chillax Wax	-0.305	1.065	-0.29	0.775
Magnet band	-1.855	1.036	-1.79	0.073
Magnet leash	0.628	1.236	0.51	0.612
Rpela	-1.337	1.047	-1.28	0.202
Surf+	-4.906	1.088	-4.51	< 0.001

The distance between the shark and the bait, and the number of passes, increased when the *Surf+* was used compared to the control board, but these variables were not affected by the other deterrents (Figs. 4, 5). The shark's distance to the board increased to 2.6 ± 0.1 m when the *Surf+* was active compared to 1.6 ± 0.1 m with the control board and 1.3 ± 0.1 to 1.8 ± 0.1 m with the other deterrents. The top-ranked model ($wAIC_c$ = 0.72) included deterrent and explained ~ 6.7% of the variance (Table 5). Again, the *Surf+* had the largest effect on the number of passes (0.14) compared to the other deterrents (-0.005 – 0.003) (Table 6).

The mean number of passes per trial was highest when the *Surf+* was active (4.7 ± 0.5), while the number of passes with the other deterrents (2.3 ± 0.3 to 3.1 ± 0.4) was similar to the control board (2.6 ± 0.3). The top-ranked model ($wAIC_c$ = 0.53) included deterrent and trial, with the deterrent and trial components together explaining ~ 5.5% of the variance (Table 7). However, trial did not strongly affect the number of passes because the next-ranked model did not include trial, had a slightly lower $wAIC_c$ (0.36), a similar R_m, and the trial coefficient was small (0.002). Again, the *Surf+* had the largest effect on the number of passes (0.176) compared to the other deterrents (-0.04 – 0.005) (Table 8).

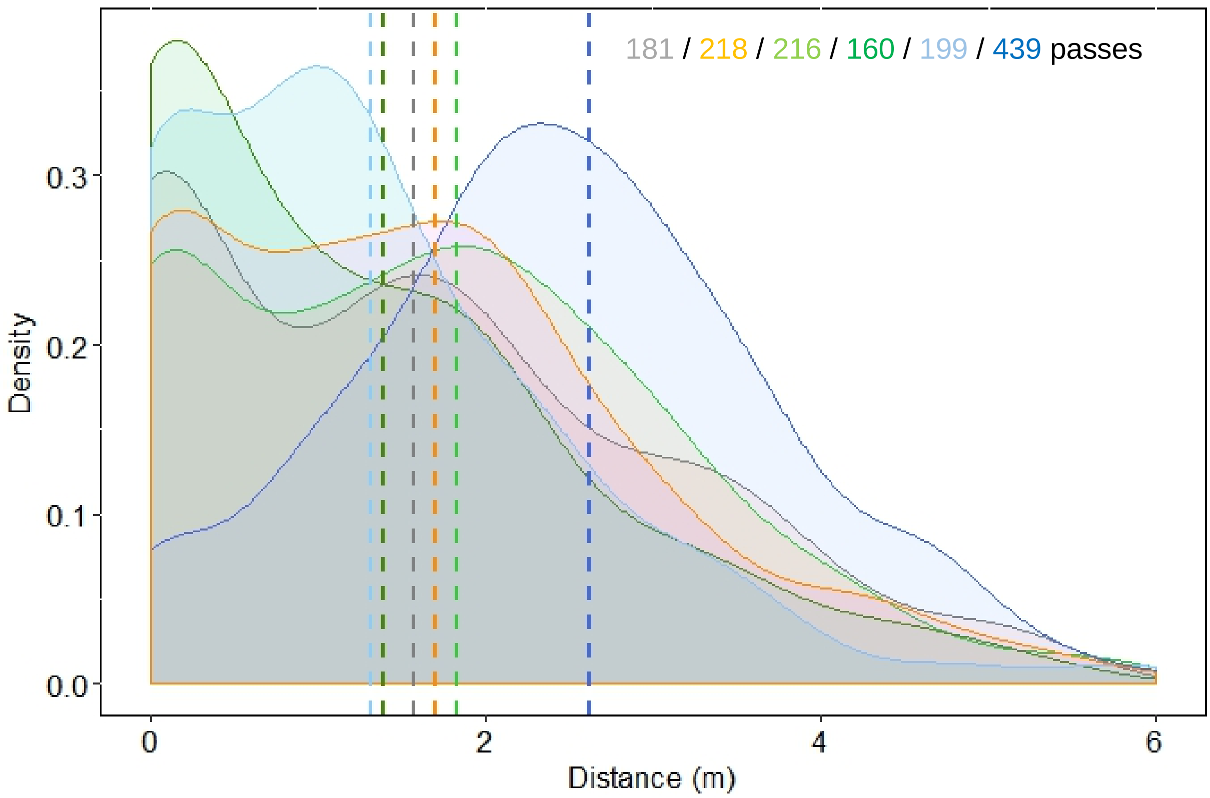

Figure 4. Density distribution of the distance between white shark and the bait. Dash lines represent means for each deterrent. Grey = control; orange = *Chillax Wax*; light green = *magnet band*; green = *magnet leash*; light blue = *Rpela*; blue = *Shark Shield (Ocean Guardian) Freedom+ Surf*. Coloured numbers indicate the number of passes from which the density distributions were calculated and match the colours of the deterrents.

Table 5. Summary of models estimating the effects of deterrents on the distance between white shark and the board. *k* = number of model parameters; AIC_c = Akaike's information criterion corrected for small sample size; ΔAIC_c = difference in AIC_c between the current and the top-ranked model; $wAIC_c$ = model probability; R_m = marginal (fixed effects) R^2. All models include shark ID as a random effect a Gaussian error distribution (log link).

Model	***k***	**AIC_c**	**ΔAIC_c**	**$wAICc$**	**R_m**
distance ~ deterrent	8	109.48	0.00	0.72	6.68
distance ~ deterrent + trial	9	111.42	1.94	0.28	6.66
distance ~ 1 (intercept-only)	3	164.85	55.37	< 0.01	-
distance ~ trial	4	166.15	56.67	< 0.01	0.18

Table 6. Estimated deterrent level coefficients (β) and their standard errors (SE), z-values of factors included in the top-ranked model (distance ~ deterrent; Table 5), and the individual coefficient Type I error estimate (P).

Level	β	SE	z
intercept	3.181	0.032	98.34
Chillax Wax	-0.005	0.036	-0.14
Magnet band	0.003	0.034	0.09
Magnet leash	-0.014	0.039	-0.37
Rpela	-0.046	0.034	-1.38
Surf+	0.140	0.031	4.54

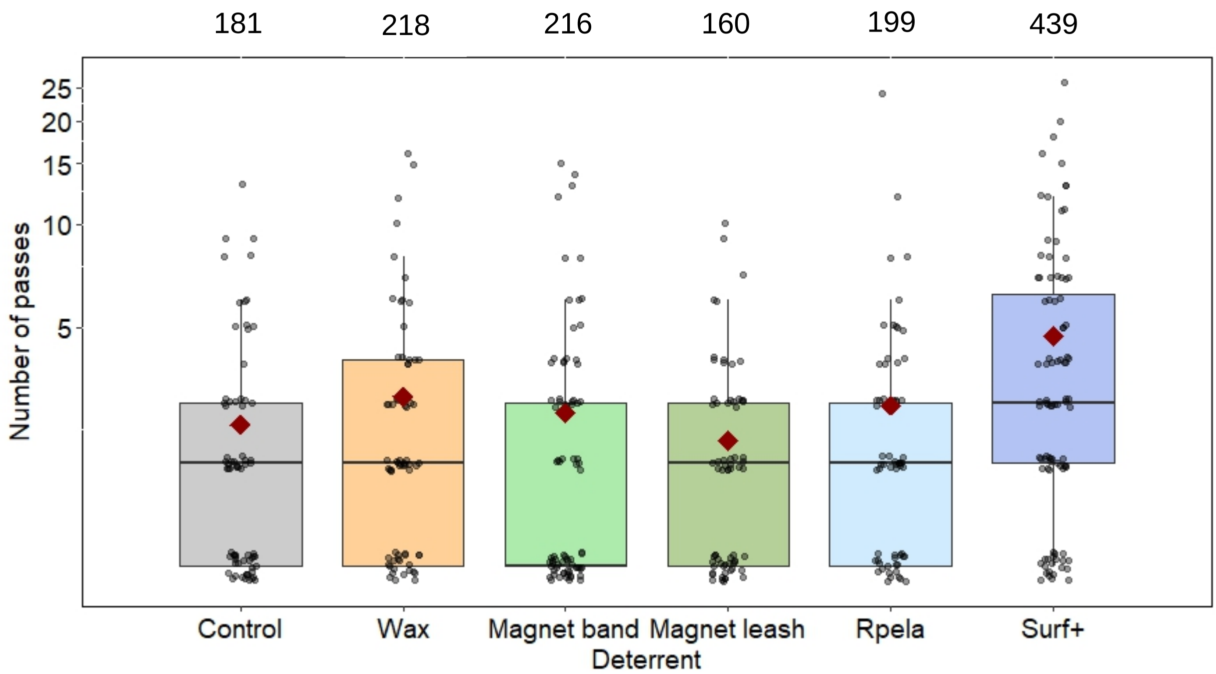

Figure 5. Number of passes per trial and shark during 15-minute trials (grey circles; with small 'jittering' to improve clarity). Median values are indicated by the horizontal bar; length of the box is the inter-quartile range; whiskers represent quartiles; circles are data points; and red diamond is the mean. Y-axis shown on the $\log_{10}$ scale. Grey = control; orange = *Chillax Wax*; light green = *magnet band*; green = *magnet leash*; light blue = *Rpela*; blue = *Shark Shield (Ocean Guardian) Freedom+ Surf*. Numbers indicate total number of passes.

Table 7. Summary of models estimating the effects of deterrents on the number of passes by white sharks towards the board. k = number of model parameters; AIC_c = Akaike's information criterion corrected for small sample size; ΔAIC_c = difference in AIC_c between the current and the top-ranked model; $wAIC_c$ = model probability; R_m = marginal (fixed effects) R^2. All models include shark ID as a random effect and a Gaussian error distribution (log link).

Model	***k***	**AIC_c**	**ΔAIC_c**	**$wAIC_c$**	**R_m**
passes ~ deterrent + trial	9	201.93	0.00	0.53	5.48
passes ~ deterrent	8	202.69	0.77	0.36	4.43
passes ~ deterrent + trial + deterrent*trial	14	205.64	3.72	0.08	7.06
passes ~ trial	4	209.52	7.59	0.01	0.93
passes ~ 1 (intercept-only)	3	210.05	8.12	0.01	-

Table 8. Estimated deterrent level coefficients (β) and their standard errors (SE), z-values of factors included in the top-ranked model (passes ~ deterrent + trial; Table 7), and the individual coefficient Type I error estimate (P).

Level	**β**	**SE**	***z***
intercept	-0.408	0.056	-7.35
Chillax Wax	0.050	0.057	0.88
Magnet band	0.009	0.056	0.15
Magnet leash	-0.034	0.057	-0.60
Rpela	0.032	0.058	0.55
Surf+	0.176	0.056	3.16
Trial	0.002	0.001	1.64

The time it took to interact with the bait ranged from 3.11 ± 0.44 minutes (*Magnet leash*) to 4.64 ± 1.01 minutes (*Surf+*) and was not affected by the deterrents (Fig. 6), with only the third-ranked model ($wAIC_c$ = 0.03; R_m < 3%) including deterrent (Table 9).

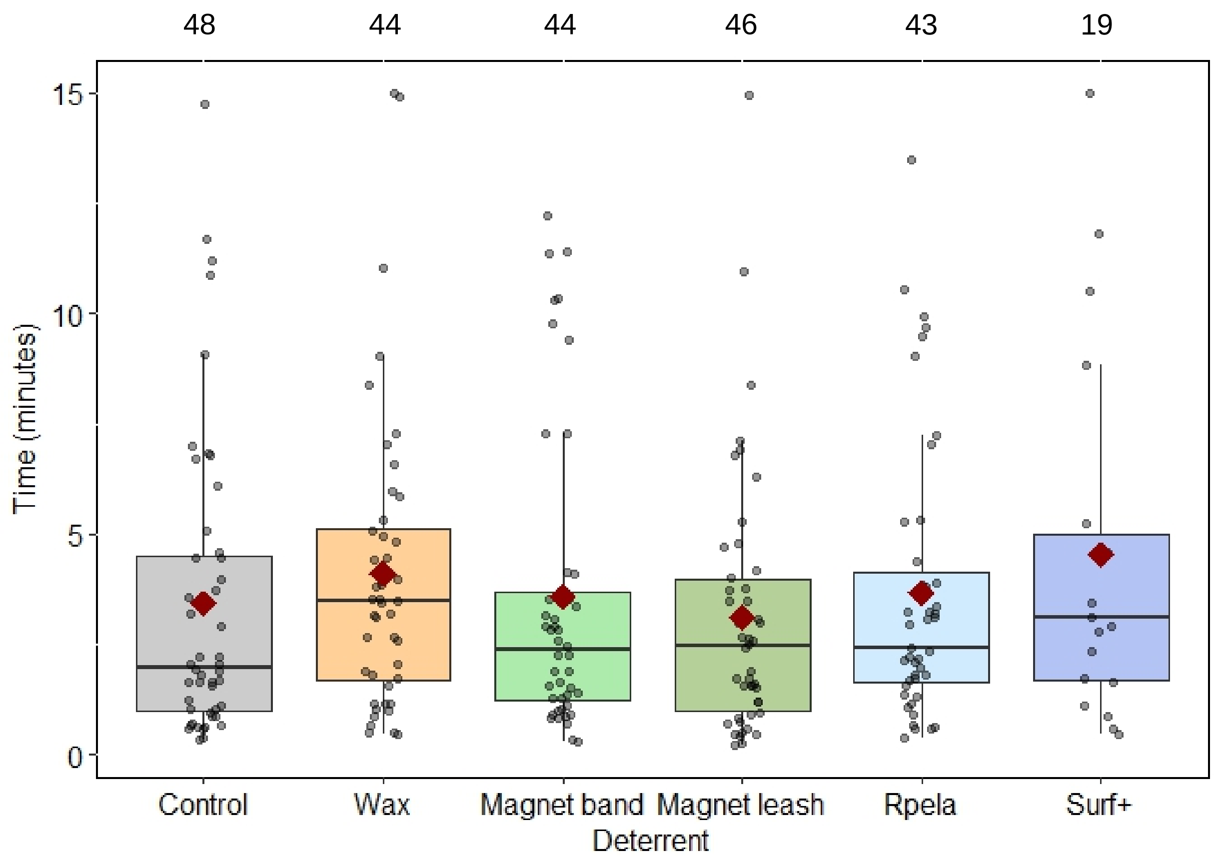

Figure 6. Time taken (minutes) for white sharks to touch or bite the board or bait (grey circles; with small horizontal 'jittering' to improve clarity). Median values are indicated by the horizontal bar; length of the box is the inter-quartile range; whiskers represent quartiles; circles are data points; and red diamond is the mean. Grey = control; orange = *Chilli Wax*; light green = *magnet band*; green = *magnet leash*; light blue = *Rpela*; blue = *Shark Shield (Ocean Guardian) Freedom+ Surf*. Numbers indicate the number of trials during which shark touched or bit the board or bait.

Table 9. Summary of models estimating the effects of deterrents on the time it took white sharks to touch or bite the board or bait. k = number of model parameters; AIC_c = Akaike's information criterion corrected for small sample size; ΔAIC_c = difference in AIC_c between the current and the top-ranked model; $wAIC_c$ = model probability; R_m = marginal (fixed effects) R^2. All models include shark ID as a random effect and a Gaussian error distribution (log link).

Models	***k***	**AIC_cAICc**	**ΔAIC_c**	**$wAIC_c$**	**R_m**
time ~ 1 (intercept-only)	3	626.95	0.00	0.48	-
time ~ trial	4	627.03	0.08	0.46	1.28
time ~ deterrent + trial	9	632.69	5.73	0.03	2.98
time ~ deterrent	8	632.77	5.82	0.03	1.73
time ~ deterrent + trial + deterrent*trial	14	637.41	10.46	< 0.01	5.20

We observed no clear patterns of temporal variation through the trials from the top-ranked models or from plotting the number of passes trial^{-1} or time to interact with the bait (Figs. 7, 8). Only one model had *trial* included in the top-ranked model, but it was not strongly supported compared to the second-ranked model and its goodness of fit was small. Behaviour of the sharks that interacted with the bait in > 15 trials showed that the *Surf+* typically led to more passes and increased distance from the deterrent relative to controls. Neither of these variables consistently increased or decreased across sharks, supporting the lack of temporal effect.

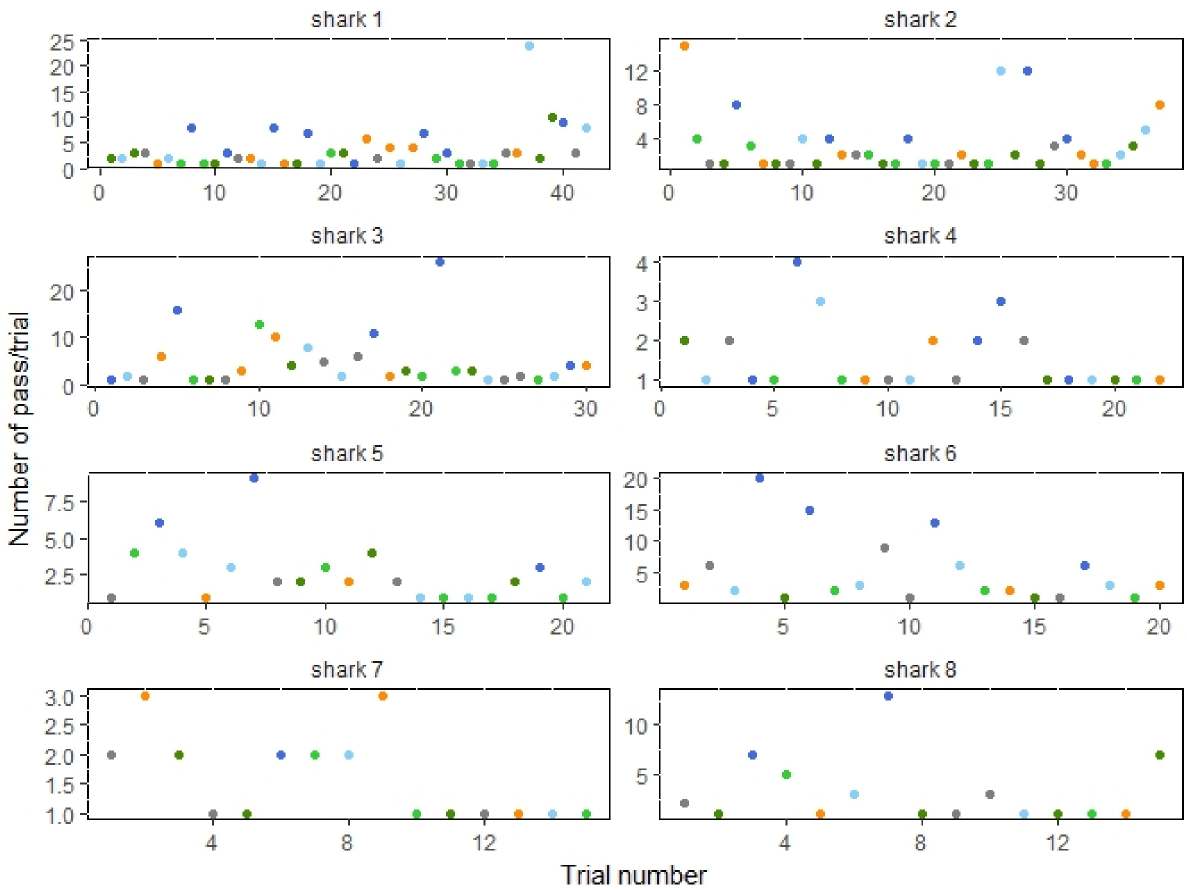

Figure 7. Number of passes during the 15-minute trials for the eight white sharksthat interacted with the boards on 15 trials or more. Grey = control; orange = *Chillax Wax*; light green = *magnet band*; green = *magnet leash*; light blue = *Rpela*; blue = *Shark Shield* (*Ocean Guardian*) *Freedom+ Surf*.

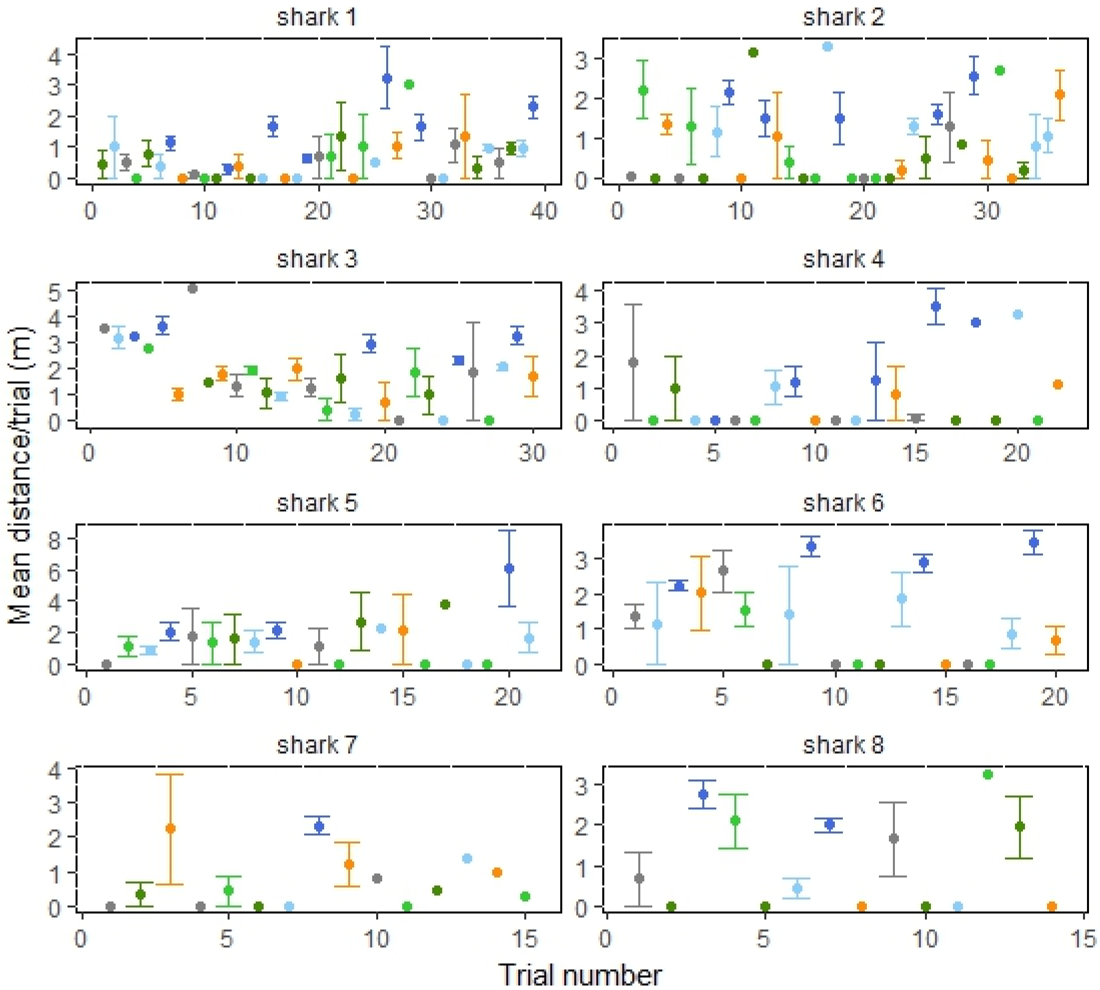

Figure 8. Mean distance between white shark and the bait for the eight sharks that interacted with the boards on 15 trials or more. Error bars represent standard errors. Grey = control; orange = *Chillax Wax*; light green = *magnet band*; green = *magnet leash*; light blue = *Rpela*; blue = *Shark Shield* (*Ocean Guardian*) *Freedom+ Surf*.

8.1 Power analysis

Based on the 297 successful trials (~ 50 per deterrent) and the variance structure of these, the *deterrent* effect became detectable when we increased the effect size relative to the controls by between 10 and > 50% (Fig. 9). For distance to the bait, the smallest detectable effect-size increase was 15% for *magnet band*, and the largest was for *Rpela* at 35% (Fig. 9). For time to feeding, the smallest increase required to detect a deterrent effect was 15% for *Chillax Wax* and *Surf+*, whereas it was > 50% for *magnet band* (Fig. 9). Finally, for the number of passes, the increase in effect size required was much larger (30% for *Chillax Wax* and *Rpela*, and 50% for *magnet leash*) (Fig. 9).

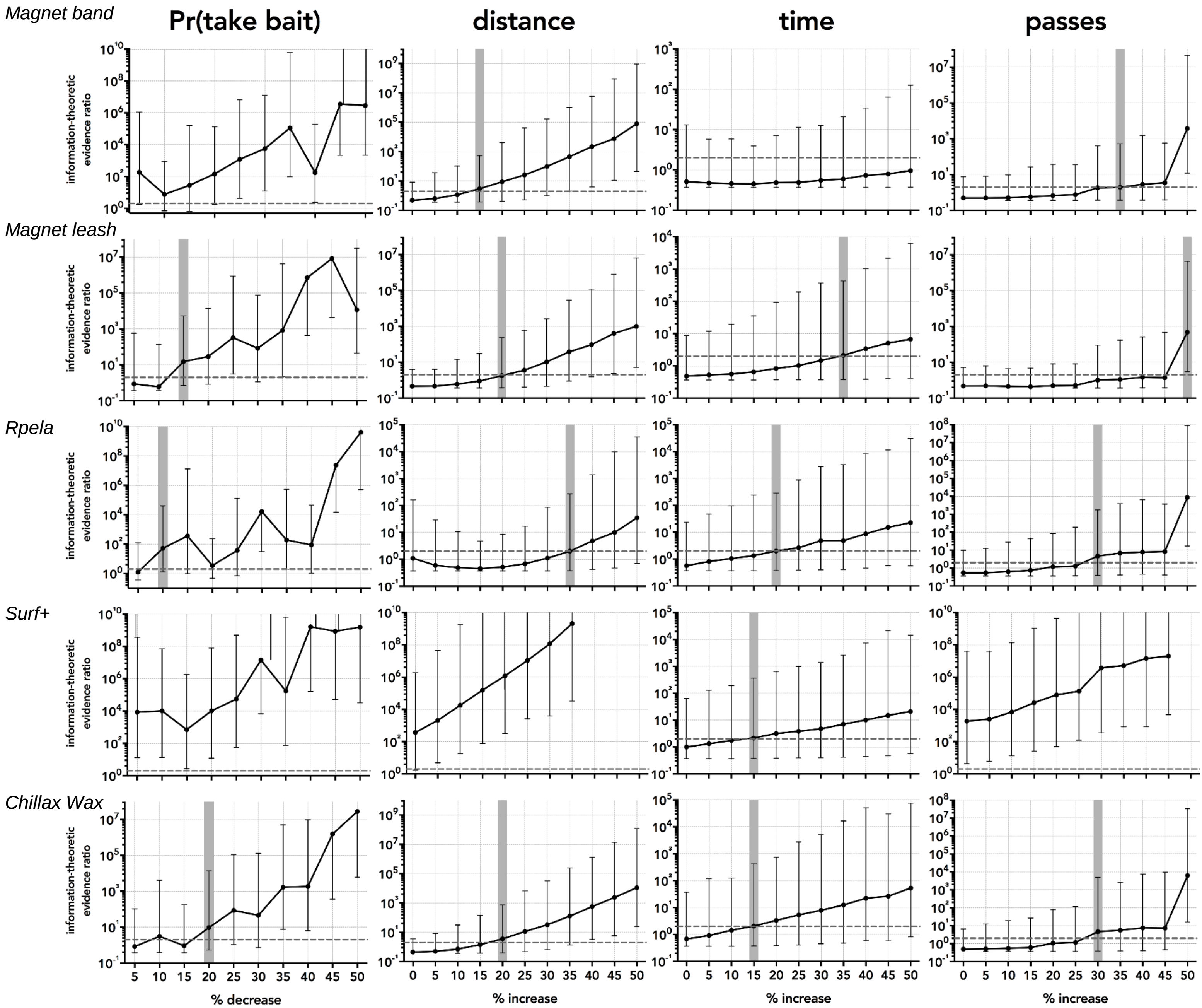

Figure 9. Information-theoretic evidence ratio of model 3 (response ~ deterrent + shark ID random effect) versus the intercept-only model (i.e., wAIC$_c$ of model 3 ÷ wAIC$_c$ of the intercept-only model) for the five deterrent-control pairs and for the four responses of proportion of bait taken (Pr(take bait) - far left column), distance to bait (left column), time to feeding (right column), and number of passes (far right column), relative to a percentage increase in the effect size relative to the control in increments of 5% from no increase (0) to 50%. The resampled (1000 times) 95% confidence limits for each percentage increment are indicated by black error bars. Dashed horizontal black line shows the threshold evidence ratio of 2 where model 3 is at least twice as likely to be the true model compared to the intercept-only (i.e., no deterrent effect) model; this is indicated as a vertical horizontal shaded area for each combination and response. Note that we detected a deterrent effect for *Surf+* (distance and number of passes), so the power analysis indicates an existing effect.

9. DISCUSSION

Although previous studies have assessed the effectiveness of some personal deterrents, ours is the first to investigate deterrents developed for surfers. We successfully quantified the effectiveness of a combination of deterrents, including new products based on technology thought to affect shark behaviour (*Shark Shield* [*Ocean Guardian*] *Freedom+ Surf* and *Rpela*), devices that have never been scientifically tested (*SharkBanz bracelet* and *leash*), and novel products (*Chillax Wax*). Our study reveals that while one of the deterrents reduces the probability of white sharks consuming the bait (*Surf+*), the other four deterrents had limited effects on white shark behaviour.

The *Surf+* had the strongest effect, reducing the percentage of baits taken from 96% to 40%. This increased the number of passes as sharks continued to attempt taking the bait. The other deterrents had limited effects on either the distance to the bait or the number of passes. This suggests that white sharks were not deterred from interacting with the board. Even the *Surf+*, which was the most effective deterrent, did not have a substantial effect on sharks unless they were near, as shown by the short distance from which sharks reacted to this deterrent (~ 1.7 m). Although the *Surf+* affected shark behaviour and reduced the probability of the bait being touched or taken, this deterrent failed to stop sharks on 40% of the trials. Several studies have previously tested the effectiveness of electric deterrents on white sharks and shown various success (Huveneers et al. 2013b, Kempster et al. 2016, Smit and Peddemors 2003). The first study assessed *SharkPOD* (a product no longer available) and concluded that the probability of an attack was reduced from 0.70 to 0.08 when the deterrent was active (88% decrease) (Smit and Peddemors 1990). More recently, two studies tested the *Freedom7* and highlighted discrepancies in the effectiveness of the device that was related to the bait placement and distance to the electrodes. When the bait was placed next to one electrode, there was an 83% reduction in the proportion of sharks interacting with the bait, concurring with Smit and Peddemors (2003). In Huveneers et al. (2013b), the bait was located ~ 2–3 m away from the deterrent to reproduce the intended distance between the centre of the deterrent's electric field and the head of a user. In this situation and in contrast to Smit and Peddemors (2003) and Kempster et al. (2016), the *Freedom7* did not have a significant effect on the proportion of times the bait was consumed (Huveneers et al. 2013b). However, a behavioural response was observed with sharks staying farther away when the *Freedom7* was active.

While the waveform and electric field produced by all *Ocean Guardian* products are not different, electrode configuration varies. This results in differences in the maximum field produced and in the distribution of the electric field relative to the body of the person using the device and likely explains the contrasting results across previous studies. Combined, Huveneers et al. (2013b), Smit and Peddemors (2003), Kempster et al. (2016), and this study, show that the effective deterrent range of the Ocean Guardian waveform depends on how far the bait is from the electrodes, highlighting the importance of carefully considering the position of the electrodes in relation to the object or person intended to be protected by the device. The locations of the *Surf*+ electrodes underneath the surfboard ~ 1.2 m apart ensure that surfers are contained by the electric field produced by the deterrent. This electrode configuration is therefore more likely to be suitable than previous products where electrodes were located behind the person wearing the device (e.g., *Freedom7* and *Surf7* — no longer available).

The positions of the *Rpela* electrodes are similar to the *Surf*+; however, the *Rpela* produces an electric field at a higher voltage gradient than the *Surf*+ (200 V vs. 115 V). Therefore, we expected that the *Rpela* would perform similarly or better than the *Surf*+. However, our experimental observations did not support this and instead found limited effect when the *Rpela* was active. The *Rpela* was the only other deterrent to which sharks reacted more than the control board (9% vs. 2% of the passes), although this difference was not supported statistically (i.e., we cannot differentiate the two). Mapping the electric field emitted by these two products shows that the *Rpela*'s electric field does not reach as far as the *Surf*+'s despite its stronger voltage gradient. The *Surf*+ had a higher maximum effective distance at 3 V m^{-1} than the *Rpela* (0.7 vs. < 0.5 m) (Hart and Ryan 2018), which might explain the differences in behaviour we observed. The ability to further increase the voltage gradient of an electric deterrent is limited because it can cause involuntary muscle spasms of the person wearing it (Bikson 2004). Kempster et al. (2016) proposed that it could be possible to increase the effectiveness of an electric deterrent by altering the frequency of the electric field discharge. The *Surf*+ discharges at a frequency of ~ 1.6 Hz, while *Rpela* has a frequency of ~ 14.5 Hz. As a result, the duration of the pulse is also much shorter in the *Rpela* (~ 0.2 ms) than the *Surf*+ (~1.5 ms). Based on the observed difference in effectiveness between the *Rpela* and *Surf*+, the short pulse duration might be less effective at deterring sharks. Alternatively, the longer frequency of the *Surf*+ might be more likely to shock an approaching shark because the animal is able to come closer to the deterrent between pulses, thus feeling the electric pulse more strongly. The pulse duration and frequency are tightly linked, so it is not possible to assess which contributed the most to the discrepancy in shark behaviour between the *Rpela* and *Surf*+. The two deterrents also differ in the type of currents discharged (*Rpela*: direct current; *Surf*+: alternative current), which might have also affected the extent of the sharks' responses. Whether the lower effectiveness of the *Rpela* is due to the difference in field propagation, pulse type, duration, or frequency is unknown, but the discrepancy between the two products and differences within the *Ocean Guardian* products show the complexity of electric deterrents and the need to ensure that adequate testing is done for all new products before commercial release.

Neither the *SharkBanz bracelet* nor *leash* affected the behaviour of white sharks or reduced the percentage of baits taken. These products rely on permanent magnets (Grade C8 barium ferrite; $BaFe_2O_4$), which have previously been used to overwhelm the electromagnetic sense of sharks. Unlike temporary magnets or electromagnets, permanent magnets either inherently create their own persistent magnetic field or retain magnetism upon initial magnetization and do not require an electrical supply. Elasmobranchs have a detection threshold in the order of nanovolts (e.g., Jordan et al. 2011, Kajiura and Fitzgerald 2009), so because the voltages associated with the induction-based mechanism of the magnets substantially exceed this threshold, they theoretically can elicit deterrent responses due to the strength of the stimulus. Permanent magnets project detectable magnetic fields underwater that produce sufficient magnetic fields to elicit avoidance in a range of species, including hammerhead (*S. mokarran* and *S. lewini*), lemon (*Negaprion brevirostris*), Australian blacktip (*Carcharhinus tilstoni*), grey reef (*C. amblyrhynchos*), bull (*C. leucas*), milk (*Rhizoprionodon acutus*), speartooth (*Glyphis glyphis*), and white sharks (Connell et al. 2015, O'Connell et al. 2018, O'Connell et al. 2014a, O'Connell et al. 2014b, O'Connell et al. 2011, O'Connell et al. 2010, Rigg et al. 2009, Robbins et al. 2011). However, the distance from which sharks reacted to magnets in those studies was small, typically <0.5 m (O'Connell et al. 2014a, Rigg et al. 2009) and the effectiveness of the magnets decreased with increasing shark motivation (Robbins et al. 2011). Barium-ferrite permanent magnets generate a flux that decreases at the inverse cube in relation to the distance from the magnet, from near 1000 G at the source to an amount comparable to the Earth's magnetic field (0.25 – 0.65 G) at distances of 0.30 – 0.50 m (O'Connell et al. 2014), showing how rapidly the magnetic field decreases. Sharks would therefore need to be < 0.30 m for such magnets to act as real deterrents. This suggests that magnets are unlikely to be effective at deterring sharks because they will only protect close to the magnet, limiting their applicability as personal deterrents unless stronger magnets can be used or many magnets are positioned on the surfer or board. The latter would add weight to the board and diminish its performance. However, several studies have shown the potential use of strong magnets in combination with visual deterrents to prevent sharks from entering some areas (e.g., beaches, embayments) (O'Connell et al. 2018, O'Connell et al. 2014b). A more powerful alternative to ferrite magnets is the neodymium-iron-born ("rare earth") magnet. This is the strongest permanent magnet currently available, with surface field strengths much higher than the avoidance response thresholds identified for sharks (Rigg et al. 2009). Their greater strength gives them potential as line-based shark repellents because smaller magnets can be used.

Chillax Wax also had limited effect on the behaviour of white sharks and on the likelihood of sharks taking the bait. *Chillax Wax* purports to mask the odour of surfers by overwhelming the shark's olfactory organs with odour atypical of their natural prey. This combination of eucalyptus, chilli, cloves, cayenne pepper, neem, tea tree oil, citronella, coconut, and beeswax is placed on the deck of surfboards, and the odour is dispersed as surfers paddle or sit on their board. We determined that *Chillax Wax* was not enough to dissuade an approaching shark to take the bait. This might have been caused by the odour of the berley and bait used to run the trials, which could have masked that of the wax. Berley and bait were necessary however to complete sufficient trials. None of the ingredients used in *Chillax Wax* is an established sharks repellent by itself, so the product is more likely to reduce the likelihood of a shark investigating a surfer than dissuading a shark from biting one. More experimental work using *Chillax Wax* is still required to test whether it can reduce the probability of a shark investigating a surfer without relying on bait or berley, although this could be challenging.

Although the *Surf*+ reduced the percentage of interactions with the board and bait, it did not completely prevent these interactions. Much of the variation in the models was explained by shark ID (up to three times; results not shown), indicating that behavioural responses were highly variable across individuals. Such individual variations might explain why the *Surf*+ did not stop interactions during all trials. The reason for this variation is unknown and might arise from a combination of motivation, different natural feeding histories, dominance hierarchies, individual experiences, or behavioural syndrome (consistency of responses across situations). Huveneers et al. (2013b) and other (Huveneers et al. 2013a, Towner et al. 2016) also noted similar intra-specific variability in white sharks, emphasising the need to ensure that shark deterrents are tested on a sufficient number of individuals to identify and account for such individual variability. The *Surf*+ produced a behavioural reaction in some sharks, but certainly cannot be relied on to prevent shark bites in all situations.

White sharks might have become acclimatised to the deterrent through habituation, or conditioning to the positive rewards resulting from consumption of the bait. Such temporal correlation and decrease in the effectiveness of an electro-magnetic field has previously been observed in Galapagos, sandbar (*C. plumbeus*), lemon, and great hammerhead sharks (Brill et al. 2009, Connell et al. 2015, Robbins et al. 2011) and by Kempster et al. (2016) on white sharks. The latter showed that average proximity decreased with every encounter and suggested that sharks were becoming more tolerant of the electric field. We examined this potential phenomenon, but there was no strong evidence supporting temporal changes in the number of passes and minimal distance. While trial appeared in the top-ranked model for the number of passes, the total model weight ($w\text{AIC}_c$) did not strongly support this model over the model not including trial (wAIC$_c$ difference between models = 0.17) and the percentage of variance explained increased by only 1%. The *trial* coefficient was also small (0.002) and the figure showing the number of passes across trials for the eight sharks interacting with the bait did not show clear trends that suggest any temporal variation. This lack of temporal correlation has also been observed in other species (Jordan et al. 2011, Rigg et al. 2009). It is likely that the small number of food rewards provided and the alternation of positive and negative reinforcements from the various deterrents being randomly activated for each trial prevented habituation.

Although our study did not show that the *magnet band* and *leash*, *Chillax Wax*, and *Rpela* had any observable effects on the response of white sharks, it is possible that these deterrents have small effects that we could not detect with the 50 trials. The estimated minimum effect size across responses shows that our study design would not have been able to detect a difference of a < 30% increase in the number of passes and a 15–35% increase in the distance between the shark and the bait. This does not infer that additional trials would have necessarily resulted in our models detecting an effects from these deterrents; rather it means that more than 50 trials would be required to detect changes of a magnitude < 15% greater than we observed, if there were any effects. Although the number of trials in our design was insufficient to detect effects <15 %, the public likely expects shark deterrents to reduce the probability of being attacked or bitten by > 15%, which our study was able to detect. However, if other agencies require testing for smaller effect sizes, greater samples sizes than what we tested would be required.

For the time it took sharks to interact with the bait, the minimum detectable effect sizes were 15% increase (*Surf+* and *Chillax Wax*), but > 50% for *magnet band*. Sharks were likely to respond to the odour from the bait and approach it at different times through the trial, affecting our ability to estimate accurately the amount of time individual sharks took to consume the bait. For example, a shark sighted around the testing equipment might leave the area soon after the trial begins, while another shark might first be observed towards the end of the same trial and rapidly consume the bait. To account for this, we calculated time to feeding based on individual shark's first approach instead of the start of the trial. This could also be biased because sharks could be within the vicinity of the testing equipment prior to being sighted. We therefore only presented time since start of the trial to show how long it took for a shark to take the bait, acknowledging that this variable might be influenced by our ability to detect the first arrival time of individuals sharks to the study area and within the vicinity of the testing equipment.

Since it was not possible to know the location of all sharks present at the study site during our experiments, we could not account for possible interactions between sharks. However, while we observed several sharks within 20 m of the equipment, more than one shark rarely approached the bait simultaneously. Our results could also have been potentially influenced by the study site being where cage-diving usually occurs and our reliance on berley to attract sharks. The need for sufficient replicates required choosing a place where a large number of sharks aggregate and using berley to attract them. We also acknowledge that testing at a pinniped colony using natural prey as an attractant in an area where white sharks feed presents an extreme situation, is a different context to that of most swimmers or surfers, and that behavioural response of sharks might depend on context (Huveneers et al. 2013b). In the case of the *Surf+*, its ability to reduce the percentage of bait taken might improve when sharks are less motivated, whereas the other deterrents could begin to demonstrate effects. Although future research is necessary to provide more insight into why white sharks seize humans, white shark interactions with humans are highly variable. They can range from situations where a shark does not closely approach a person, to targeted strikes potentially motivated by hunger. Therefore, the context in which deterrents are tested should not be directly extrapolated to all shark-bites situation and our results should be presented in this context.

The rise in the number of shark bites worldwide and in Australia has led to global development of shark-mitigation measures and the commercial availability of personal deterrents. Our study clearly shows that while some products are capable of affecting the behaviour of sharks and can reduce the risk of a shark bite, others did not have the advertised outcome. Manufacturers should consider these results to assess the suitability of their products and gauge whether changes are required to ensure their intended performance. Our results will allow private and government agencies to make informed decisions about the use of these devices for occupational activities and enable the public to make appropriate decisions about the use and suitability of these five products.

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