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ORIGINAL PAPER

Are Caribbean reef sharks, *Carcharhinus perezi*, able to perceive human body orientation?

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Abstract The present study examines the potential capability of Caribbean reef sharks to perceive human body orientation, as well as discussing the sharks' swimming patterns in a person's vicinity. A standardized video method was used to record the scenario of single SCUBA divers kneeling in the sand and the approach patterns of sharks, combined with a control group of two divers kneeling back-to-back. When approaching a single test-subject, significantly more sharks preferred to swim outside the person's field of vision. The results suggest that these sharks are able to identify human body orientation, but the mechanisms used and factors affecting nearest distance of approach remain unclear.

Keywords Approach · Humans · Swim patterns · Sharks

Introduction

The perception of the body form and size of a member of a prey species, as well as its direction of locomotion, is a prerequisite for predator success (e.g., Hambright 1991; Domenici and Blake 1997; Scharf et al. 2000). Studies confirm this is true for sharks when they hunt or stalk their prey (e.g., Heithaus et al. 2002). Descriptions of a shark's approach to typical prey species as well as humans indicate that sharks prefer to avoid the field of vision of their prey, i.e., a shark would tend to approach from *behind* a person (e.g., Baldridge 1988; Collier 1992; Levine 1996; Byard et al. 2000). These observations underlie the assumption that sharks are capable of identifying human body orientation and can use such information in a self-serving manner. However, rigorous tests to evaluate this assumption have never been conducted.

Prior to divers populating marine shore areas, sharks were rarely exposed to humans. Such a short and localized exposure is insufficient for sharks to learn human body orientation, especially under conditions that do not include direction of locomotion as a clue. Although it is known that some non-human primates, marine mammals, and canines can identify human body and face orientation (Call et al. 2003; Gácsi et al. 2004; Kaminski et al. 2004), the "direction of another's attention" (Itakura and Anderson 1996; Povinelli and Eddy 1996; Hare et al. 2000), or simply follow gaze and eye visibility (Gácsi et al. 2004; Pack and Herman 2004), these species are either evolutionarily more closely related to humans or trained to make the differentiation (e.g., McKinley and Sambrook 2000; Pack and Herman 2004).

The only study where a human effect was examined in the vicinity of sharks was done by Ritter and Amin (2012). Although that study focused on human positioning when close to sharks, it showed that human presence does affect the swimming behavior of these animals, and e.g., larger sharks are more cautious in the vicinity of humans than smaller ones.

To deepen the understanding of how sharks select an approach pattern when interacting with humans, we designed a test to evaluate whether sharks show a measurable preference based on body orientation when approaching a person. Furthermore, we tested whether

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sharks choose a certain swim pattern while within the vicinity of a human being.

Materials and methods

We conducted the tests of potential approach preference of sharks with regard to human body orientation in the Northern Abaco Islands, Bahamas, on 8 days between July 7 and 24, 2009. Later on, several days were excluded due to the chosen criteria (see below for further explanations). All tests took place in the morning hours between 10:00 and 12:00, since dives in the past showed that hardly any sharks remained at the location during the afternoon hours.

To keep the meteorological influences to a minimum, data collection only took place (1) under clear skies; (2) when the underwater visibility exceeded 30 m, to give sharks ample time and distance to observe the scenario before entering the recording area; and (3) where there was no current, except when caused by tidal effects, to exclude current-influenced approach patterns of the sharks entering the recording area.

Study site

The test site consisted of an open reef area with a sandy bottom and an average depth of 12 m. The sharks could freely come and go and were able to see the test-subject(s) from at least 30 m from all sides.

Safety considerations

The Shark Research Institute, Princeton, NJ, USA, supervised all studies to ensure full accordance with safety requirements when among sharks.

Based on a risk assessment performed when creating the setup, and due to the inherent risks of shark interactions, we obtained informed consent from all participants. We also trained participants on how to react during a direct shark encounter, should a shark attempt to bite (Ritter 2006). Furthermore, the videographer acted as the safety diver, instructed to interfere should a shark change its behavior beyond known approach patterns (Ritter 2006).

No special permission was required for this type of study within Bahamian waters.

Chosen shark species and population size

As a test species, we chose the Caribbean reef shark, *Carcharhinus perezi*, a typical reef shark frequently encountered by divers in the Bahamas and not considered to be a dangerous species regarding incidents with humans (Shark Research Institute 2013). Caribbean reef sharks are the most common sharks around the Bahamas, representing a typical inshore, large sized, bottom-dwelling species (Compagno 1984), with a maximum size of about 300 cm but rarely exceeding 250 cm.

Caribbean reef sharks are the prime species used in several shark feeding dive tourist facilities throughout the islands of the Bahamas. The general vicinity of the chosen site was used for such a 'shark dive' until 2003, after which the diving operation ceased to exist. Due to the intervening years, and considering the size, and thus age, of the sharks present (e.g., Tavares 2009), it could be assumed that a new generation had populated the reefs by the time this study took place. While it could not be excluded that some older sharks were still around it was rather unlikely for this species (Garla et al. 2006), especially over so many years, and even more so since the Northern Abacos do not consist of isolated reefs that could increase the likelihood of site fidelity (e.g., Garla et al. 2006; Heupel et al. 2010; Bond et al. 2012). No further studies have been done with the species chosen for this project.

Due to the openness of the area, no shark was blocked in any way by the test-subject(s) while approaching or leaving the site, nor forced into any swim patterns. Furthermore, the topography allowed several sharks to be within the vicinity of the test-subject(s) without noticeably interfering with each other. The gender of all sharks swimming within the field of view of the participants was reported after every test; only females were observed during this study. Based on their body lengths, all sharks were considered to be mature.

Test setup

One diver, the test-subject, in full SCUBA gear was positioned on the sea floor in a kneeling position, looking forward. The test-subject's viewing direction was defined as the 0°-line. The two 90°-sectors abreast of the 0°-line were considered the test-subject's *front* or *field of view*. In contrast, the opposite sectors along the 180°-line were labeled the *back* or *blind area*.

The control measurement for the one-diver setup consisted of a two-diver setup where both test-subjects kneeled on the bottom, positioned back-to-back in order to eliminate the blind area. That the control group doubled in size did not matter since the baseline was to establish whether the sharks would still prefer one side over the other despite that both sides were now equal.

To keep individual human influence on sharks to a minimum, all test-subjects kept their heads facing their respective viewing direction. Test-subjects were not allowed to turn their heads to look for or visually follow sharks, as this may have influenced sharks approaching or departing the vicinity.

Data collection

In this project, the test-subjects were stationed at the sea bottom, while the videographer was positioned at the water surface directly above them. The surface position of the videographer was chosen to reduce video distortion effects and to avoid any potential interference with any of the advancing sharks, despite the fact that only sharks that swam close to the sea bottom were included. An area with a radius of 7 m was marked as the recording zone, with the test-subject(s) in the middle. Beyond that distance we could not be confident that the measured length of a shark was still accurate within 10 cm. 1-m markers were positioned all over the recording area for accurate measurements. If a shark was not swimming within 1 m (radius) of a marker, an approximation of the distance with markers closest by was made. The same measuring technique was previously used in a similar study to measure shark length and distance toward a person positioned at the surface (Ritter and Amin 2012).

Four variables were recorded: (1) shark body length; (2) the shortest distance a shark approached to the test-subject(s), expressed both as *absolute distance* and as a fraction of shark body length (BL), referred to as *relative distance*; (3) relative speed, expressed in tailbeats per second (tbs) and referred to as *tailbeat frequency*; and (4) shark swim pattern (see below for further explanations). We estimated tailbeat frequency by transforming the average time of a single tailbeat cycle from the duration of three consecutive cycles.

We gathered length and distance measurements, rounded to the nearest 10 cm, directly from videotape using Pixelstick 1.1 (Pixelated Software). We evaluated the video clips using iMovie 6.0 (Apple®), or Final Cut Pro 6.0 (Apple®) if enhancements were needed for clarification.

We refrained from tagging the sharks present. We felt that tagging alters the behavior of a shark, since an animal must first either be caught by hook or net, or has to be lured in close enough to apply a tag by harpoon or spear gun. Any of these procedures creates pain or distress among the animals (e.g., Chandroo et al. 2004; Huntingford et al. 2006; Braithwaite and Boulcott 2007); therefore, we could not exclude the possibility that such a procedure would affect a shark and later influence behavior in the vicinity of a human being during the tests.

In addition to tagging being undesirable, such a procedure would in any case not have been feasible at all since we did not know how many sharks would be present during the tests and every additional shark, not previously captured, would have to be ignored, or a subsequent capture attempted. The fact that individual sharks were not tagged led to a series of analyses to overcome pseudo-replication issues (see further below).

Test randomness

Each day, tests included four test-subjects chosen randomly from a pool of six people for the single-diver setup. Videotape collection occurred for 15 min per person, in successive order, for a total of 60 min. Likewise, for the two-diver setup, tests included two groups of two test-subjects chosen randomly from the same pool of people, and sequentially videotaped for 30 min each, for a total of 60 min, as well. We scheduled single-diver and double-diver tests randomly to avoid habituation but always on the same day, either beginning with a single-diver setup or the other way around. In addition to test-subject randomness, we also changed the location and direction of the 0°-line daily within the general area to keep potential location and setup conditioning of the sharks to a minimum.

The study included only tests with at least 10 shark encounters per 60-min test duration. We overall collected 480 video minutes for single- and double-diver setups, in which a total of 312 approaches occurred.

Test-subjects were of either gender, between the age of 18 and 40 years, and of medium height and weight. For the experimental setup, each test-subject wore a black vest and black dive suits. As long as vests and dive suits were the same color, it was not insisted that the same brand was worn, based on the assumption that people might get more nervous in unfamiliar equipment, thus adding an uncontrollable factor.

Swim pattern of sharks

Sharks entering the test area were tallied as *passing,* swimming in a straight line past the subject, or *adapting*, altering their swim pattern while in the test area. Ritter (2006, 2012) described *passing* as part of a set of approach patterns a shark can choose when approaching an unfamiliar object. *Passing distance* was the closest a shark came to a person while *passing*, reflected as the already mentioned *absolute* and *relative distance*. Similarly, a *turning point* reflected the distance at which a shark directly approaching a person veered off. During the one test-subject setup, we also measured the angle between this head-on swim direction and the 0°-line, the test-subject's viewing direction, rounded to the nearest 5°.

Data evaluation

The daily number of sharks ranged between seven and 12 individual animals. Every so often, when a shark entered the recording area, the videographer looked around and tallied all the sharks seen at that moment. However, he then refocused on the shark within the recording area and did not visually follow the other sharks in the vicinity.

All statistical analyses were performed with the Statistical Analysis System (SAS, Version 9.2) software package. Since we anticipated a higher proportion of shark approaches from the back in the single-diver setup, we used a one-tailed Fisher's Exact Test and the total of 312 shark approaches to compare approach patterns between the two setups.

Next we used a two-factor analysis of variance with interaction to compare the means of the three variables (length, distance, and relative distance) for the two factors (A = number of test-subjects, B = side of approach), where $A = 1$ or 2 and B = front or back. As a first check of the underlying assumptions, we conducted a test for normality of the underlying distribution of the data. While the regular ranks could be used for testing for main effects, a rank-based analysis of variance test for the interaction is not supported (e.g., Sawilowsky 1985, 1990; Blair et al. 1987; Sawilowsky et al. 1989; Thompson and Ammann 1989; Thompson 1991). Instead, a transformation of the raw data to normal quantiles (The Normal Scores Test) was considered as the only approach that was valid for the interaction test. This offered very similar results for main effect tests to what we would obtain by using the regular ranks (e.g., van der Waerden 1952; Conover 1999).

While the analysis of variance compared means for the variables length, distance, and relative distance, another step was to establish the presence or absence of an association between number of test-subjects, length of shark, distance of shark to test-subject(s), relative distance of shark to test-subject(s), and the side from which the shark approached (front versus back). By coding the side (0, 1), with a front approach being "1", we were able to conduct a stepwise logistic regression to predict the side of the approach. In both approaches mentioned above (analysis of variance and logistic regression), we were assuming that there were no measurement errors and that possible pseudo-replications (see below) by some sharks have negligible effect on the findings.

Pseudo-replications

The problem of possibly having some pseudo-replications within the shark samples where some sharks have been recorded more than once during the experiment was difficult to address due to not having any concrete statistical methodology available to handle such situations. However, we propose additional data analyses to consider that will strengthen the belief that our overall conclusions have a high probability of still being correct.

The main issue was the sample size possibly being inflated, so it was necessary to reduce the sample size—and the power of the statistical tests—in a meaningful way to reflect possible pseudo-replications. We were confident our observations of shark length were accurate to within 10 cm, so we decided to use the shark lengths in the following approach to reduce the sample sizes. We sorted the data by shark length for each of the four experimental settings (one test-subject is approached from the front, one test-subject is approached from the back, two test-subjects were approached from the front (for one of the two test-subjects), and two test-subjects were approached from the back (for one of the two test-subjects)), resulting in some of the sharks having tied shark lengths. All sharks approaching a test-subject from one side (front or back) that have identical lengths were considered "ties." We considered three cases by which the ties were handled:

Case 1 We assumed that all sharks in the experiment to be distinct and used the entire data set as if there was no pseudo-replications.

Case 2 We reduced the sample size by dividing the number of sharks within a group of tied sharks by two.

Case 3 We assumed that all sharks with the same shark length to be one shark.

Three research questions were then addressed in this project. (1) Was the proportion of sharks approaching a test-subject from the front equal to the proportion of sharks approaching from the back? (2) Was there a significant difference in the lengths of sharks approaching a test-subject from the front when compared with the lengths of sharks approaching from the back? and (3) Was there a significant difference in the minimum distances from the test-subjects for sharks approaching them from the front when compared with the minimum distances for sharks approaching test-subjects from the back?

Results

Research question (1) could be addressed for the one test-subject experiment in a meaningful way by obtaining the P value for the chi-square goodness of fit test, corresponding to different "sample sizes," depending on how the tied shark lengths were treated. For Case 1, there were 82 % ($N = 174$) sharks from the back, compared to 18 % ($N = 37$) sharks from the front. The chi-square test rejected the null hypothesis of equal proportions for back and front, with $P < 0.0001$. In Case 2, there were 81 % ($N = 85$) sharks from the back, compared to 19 % ($N = 20$) sharks from the front, resulting again in $P < 0.0001$. The same result was obtained if the number of sharks in a group with tied shark lengths was divided by 3. In case 3, there were 61 % ($N = 25$) sharks from the back, compared to 39 % ($N = 16$) sharks from the front, resulting in $P = 0.16$. The small sample sizes resulted in lower statistical power, and so the null hypothesis of equal proportions of sharks from the front and the back of the test-subject could not be rejected. Also considered was the experiment with two test-subjects kneeling back-to-back from each other. In cases (1), (2), and (3), the P values were 0.28, 0.57, and 1.0, respectively. The null hypothesis of equal proportions from the front and the back of the test-subjects could not be rejected, and it could be stated for the one test-subject experiment that a significantly higher proportion of sharks approached the person from the back than from the front.

As for comparing shark lengths, it was not feasible to consider the analysis of variance approach for Case 2 when the sample size had to be reduced by dropping a portion of the tied values since it was unwanted to arbitrarily pick some values for being removed. In Case 3, the two-factor analysis of variance based on normal rank scores did not result in any significant effects for shark length and for distance from test-subject. In order to be able to test for Case 2, we chose a one-tailed Fisher's Exact Test for the two factors [side of shark approach (front and back)] and shark length category (less than the median and greater or equal to the median). In the one test-subject experiment, the P values for cases 1, 2, and 3 were 0.045, 0.029, and 0.52, respectively. In the two test-subject experiment, the P values for cases 1, 2, and 3 were 0.94, 0.87, and 0.76, respectively.

Shark lengths, distance, and relative distance

The Shapiro–Wilk test resulted in the rejection of the normality claim for the three variables length, distance, and relative distance, which implied the use a normal scores version of the analysis of variance.

We considered the frequencies of shark approaches for two factors (A = number of test-subjects, B side of approach), where $A = 1$ or 2 and $B =$ front or back which resulted in the observed proportions 82 % from the back in the one-diver case, versus 55 % in the two-diver case. Comparison of these values using a one-tailed Fisher's Exact Test revealed a very small P value ($P \leq 0.0001$), indicating that there was a significant association between the number of test-subjects and the side from which the shark approached.

A two-factor multivariate analysis of variance on the normal scores (or quantiles) with Wilks' Lambda gave a multivariate test for side main effect with $P = 0.76$ while the tests for test-subject main effect showed $P = 0.097$. The interaction effect was significant with $P = 0.041$. The significant test-subject by side interaction implied we should not test for multivariate main effects, such as comparing front to back when averaging over the number of test-subjects, or comparing one test-subject to two test-subjects when averaging over both sides due to the possibility of the interaction masking main effects. A significant multivariate interaction test implied that at least one univariate test for interaction would be significant. The analysis of variance based on normal scores for the three variables length, distance, relative distance revealed the following results:

(a) Length: no factor was significant, with the test-subject by side interaction F test being borderline nonsignificant ($P = 0.057$). Testing two contrasts revealed that the mean shark lengths differed significantly (front versus back) in the one-diver case ($P = 0.020$), while they did not differ significantly in the two-diver case ($P = 0.94$).
(b) Distance: side was significant ($P = 0.034$) but the test-subject by side interaction F test was not ($P = 0.086$).
(c) Relative distance: test-subject by side interaction was significant ($P = 0.013$), required additional testing on the cell means with two contrasts. There was a significant contrast between relative distance of approach for the one-diver case (front versus back) with $P = 0.0134$ but not so in the two-diver case ($P = 0.17$).

In all three cases (*a*, *b*, *c*), the interaction test was either significant or borderline nonsignificant, which matched what was obtained with the multivariate analysis of variance.

We coded the variable side as (0, 1), with a front approach being "1", and were able to conduct a stepwise logistic regression to predict the side of the approach. A stepwise logistic regression resulted in a model with all four variables included (test-subject, length, distance, relative distance), resulting in a 70.7 % concordance rate. This means that this regression model could correctly predict the pattern of shark approaches (front versus back) in 70.7 % of all shark approaches. The main contributors to this prediction were number of test-subjects ($P < 0.0001$) and distance ($P = 0.04$), while shark length ($P = 0.17$) and relative distance ($P = 0.067$) were nonsignificant but still needed in the model, playing synergistic roles. The logistic regression approach provided additional support to our findings that it was possible to explain shark approaches (from the front or back) by considering how many test-subjects were present and by knowing the length of the sharks and the distances between them and the test-subject(s).

Summary of findings

Blind area

In the case of a single test-subject, significantly more sharks swam through the test-subject's blind area or approached the person from behind than swimming in their field of view (χ^2 test, $P < 0.0001$, $N = 211$).

Shark length

The length of sharks passing through the blind area averaged 206.0 cm (SE 1.90; $N = 174$), significantly larger than the sharks passing through the field of view ($F = 6.42$, $P < 0.05$), which averaged 195.8 cm (SE 3.90 cm; $N = 37$). With two test-subjects present, the average length for sharks for both field of views averaged 202.9 cm (SE 2.20 cm; $N = 101$).

Passing distance

The relative passing distance—absolute distance expressed in body lengths—was 1.9 BL (SE 0.04 BL; $N = 174$) for the blind area. With two test-subjects present, the relative distance was 1.8 BL (SE = 0.05 BL; $N = 101$) for both sides.

Swim patterns

With the exception of a single shark that approached head-on, all sharks passed through the field of view without any adaptation. For the blind area, the ratio between passing and adapting swim patterns was 57–43 %, respectively.

With the 0°-line as reference, the approach angle averaged 155.0° (SE 2.55°; $N = 16$) for sharks approaching from behind. The turning point distance averaged 367.9 cm (SE 10.12; $N = 16$), equaling a relative distance of 1.8 BL (SE 0.5 BL; $N = 16$). Turning point distance was not significantly different from the passing relative distance in the test-subject's visual or blind area, which averaged 2.0 BL (SE 0.5 BL; $N = 36$) and 1.9 BL (SE 0.6 BL; $N = 98$), respectively.

Relative swim speed in the vicinity of humans

The relative swim speed was the same in all scenarios: for sharks swimming in the blind area or field of view for a single test-subject, it averaged 0.5 tbs (SE 0.1 tbs; $N = 68$) and 0.5 tbs (SE 0.1 tbs; $N = 16$), respectively, as was the same when two test-subjects were present, averaging 0.5 tbs (SE 0.1 tbs) ($N = 54$).

Discussion

When swimming in close proximity to a kneeling, stationary test-subject, Caribbean reef sharks show a significant preference for a test-subject's blind area. Due to this preference, we infer that sharks seem to possess some capability to comprehend human body orientation. This significant preference is not just expressed by the fact that more sharks approached from the back within the single-diver setup. In addition, no significant differences could be identified in the two test-subject experiment. The same methodology was used to compare shark minimum distances from a test-subject, and all tests were nonsignificant. Such results may not directly be comparable with what was obtained with the two-factor analysis of variance using the complete data set since changing data from continuous measurements to frequency counts in addition to studying one factor at a time may alter the results.

Detection of human body orientation

The way predators stalk their prey or sneak up on them is often linked with the avoidance of visual contact with the quarry. Such a theory demands that a predator is capable of locating the prey's eyes or at least recognizing its viewing direction. Neither can be assumed for sharks—as the stalkers—in the vicinity of humans, especially in our design, since the chosen human position did not resemble any known prey for any shark species. Although it cannot be excluded that sharks might still be able to make a comparison to a prey species and act on it, our results do not offer explanations as to what that clue might be.

Ritter and Amin (2012) showed that human presence does affect the swim behavior of sharks and that larger animals seem to be more cautious in the vicinity of humans than smaller animals. Our results are consistent with this interpretation, showing a significant preference of the larger animals to approach test-subjects via their blind areas.

Other studies evaluating an animal's capability of determining direction of gaze of humans usually evaluated mammals (e.g., Hare and Tomasello 1999; Pack and Herman 2004). The few non-mammal species where detection of human visual direction was tested were birds, e.g., ravens, *Corvus corax* (Schloegl et al. 2008), and sparrows, *Passer domesticus* (Hampton 1994). Those results indicated that these birds were capable of using human gaze cues to some extent, probably less so than mammals. Since sharks are evolutionarily more distant from mammals than birds, can it be concluded that human gaze might not be detectable at all and that something entirely different is used by sharks to comprehend a person's viewing direction? A satisfactory answer cannot be given since the shark's perception and capability of sensory organs are much different from both birds and mammals. Similarly, the different medium could also be of importance. Characteristics of water as a solvent could facilitate a so far unknown human emission that might not carry as well in air.

Closest relative distance

The *inner circle* or *idiosphere* is the minimum distance an animal keeps between itself and a person (e.g., Martin 2007; Ritter 2012; Ritter and Amin 2012). For sharks, the radius of this comfort zone ranges between one and two body lengths. For Caribbean reef sharks, we measured an average relative distance between 1.8 and 1.9 body lengths, which confirm earlier findings. The constant distance within certain boundaries suggests that a particular sensory organ or a combination of them seem to be involved. In teleosts, the idiosphere distance generally marks the farthest distance of near-field water pressure detection (e.g., Bleekmann 1986; Sand et al. 2001; Goulet et al. 2008). For sharks, this may also be true. That the average relative distance might solely depend on vision seems unlikely, as McComb et al.(2009) determined. For blacknose sharks (*C. acronotus*), a species related to Caribbean reef sharks, the convergence distance or the useful distance of stereoscopic vision is one body length (McCombpers.com). Additionally, there was no difference between the shortest distance for a turning point, where stereoscopic vision would still be in effect, and the passing distance, where cyclopean vision is used. Although distance measurement using one eye is possible (Pettigrew 1991), we believe that the larger relative distance measured here does not seem to depend on eyesight.

Size-influenced vigilance

Ritter and Amin (2012) showed that size influenced the vigilance of sharks in relation to humans. Similarly, in our study, larger sharks seemed more careful in the vicinity of humans, indicated by their preference for using the test-subject's blind area for approaching or passing. As with the initial study of approach distances and shark length by Ritter and Amin (2012), our data suggest vigilance dictates the distance a shark dares to approach and likely reflects the flight initiation distance (e.g., Frid and Dill 2002; Stankowich and Blumstein 2005; Cooper and Frederick 2007). Likewise, the same underlying influence may dictate why direct approaches were more frequent in the blind area than in the test-subject's field of view.

Swim pattern

With the exception of one head-on approach, sharks did not adapt their swim pattern while in the field of view, but passed straight through it. Since a shark's vigilance likely determines its closest distance within the surroundings of a human being (Ritter and Amin 2012), a direct swim path through a test-subject's field of view likely indicates that the shark predetermines that distance prior to getting close. From this point of view, swim patterns within the blind area would then be less strict and open to more adaptive patterns, as suggested by the results.

Bubbles as a potential repellent to approach test-subjects from the front

Test-subjects are unfamiliar objects for sharks and so is their creation of bubbles. It is doubtful that these bubbles determined the approach patterns of the sharks since the origin of bubbles is only identifiable up close. Furthermore, sharks also show a preference to approach people from behind when the subjects hover at the surface and their faces are not submerged, and so no bubbles exist (Ritter, pers. obs.).

Could face masks have an effect in choosing the approach direction? As with bubbles, such would not be detectable should the shark be too far away. Likewise, a shark would need to understand where the eyes of a person are located, hence not just to know the body proportions be known but also how to read these proportions when presented in a kneeling object.

That the larger size of two test-subjects in the control group could have a repelling effect on the approach pattern of the sharks is also doubtful, since average relative distance remained the same as for the single-diver setup.

Potential pseudo-replications

A potential limitation was pseudo-replications. Given the fact that no tagging of sharks was used, the same shark could have swum by multiple times during the experiment. Therefore, additional statistical analyses were performed to solidify our conclusions.

(a) The usable data stemmed from five days of collecting (additional days were excluded due to the criteria of minimum number of encounters), during which we determined the percentage of approaches from the back (one test-subject) as follows: 84.4, 72.4, 82.8, 89.5, and 79 %. It is unlikely that a few sharks kept on returning to the experiment location day after day, offering additional support that the effect of possible pseudo-replications was negligible.

(b) In order to limit a possible impact of a few sharks (with pseudo-replications) and with extreme values (length), we conducted the median one-factor analysis of variance for the one-diver setup and also for the two-diver setup, separately. In the one-diver setup, the test was significant ($P = 0.024$), showing a significantly larger median shark length for back approaches than for front approaches. In the two-diver setup, the test was nonsignificant ($P = 0.18$).

These results support the findings of the analysis of variance F tests and also the findings of the logistic regression.

Outlook for further research

In the past, discussion of shark–human interaction has focused on random incidents with these animals (Ritter and Levine 2004, 2005; Ritter et al. 2008) and not on how these animals sense and interpret humans (Ritter 2012; Ritter and Amin 2012). The more research is conducted on this unknown aspect of shark behavior, the better we will understand how to cope with them in their habitat. Our discovery that a shark seems to be able to differentiate between the field of vision and non-field of vision of a human being, or comprehend human body orientation, raises intriguing questions not only about shark behavior, but also about sharks' mental capacity. To better understand the relationship between sharks and humans, additional studies, like the one presented here, are a priority.

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