

# Cryptic habitat use of white sharks in kelp forest revealed by Animal-borne video

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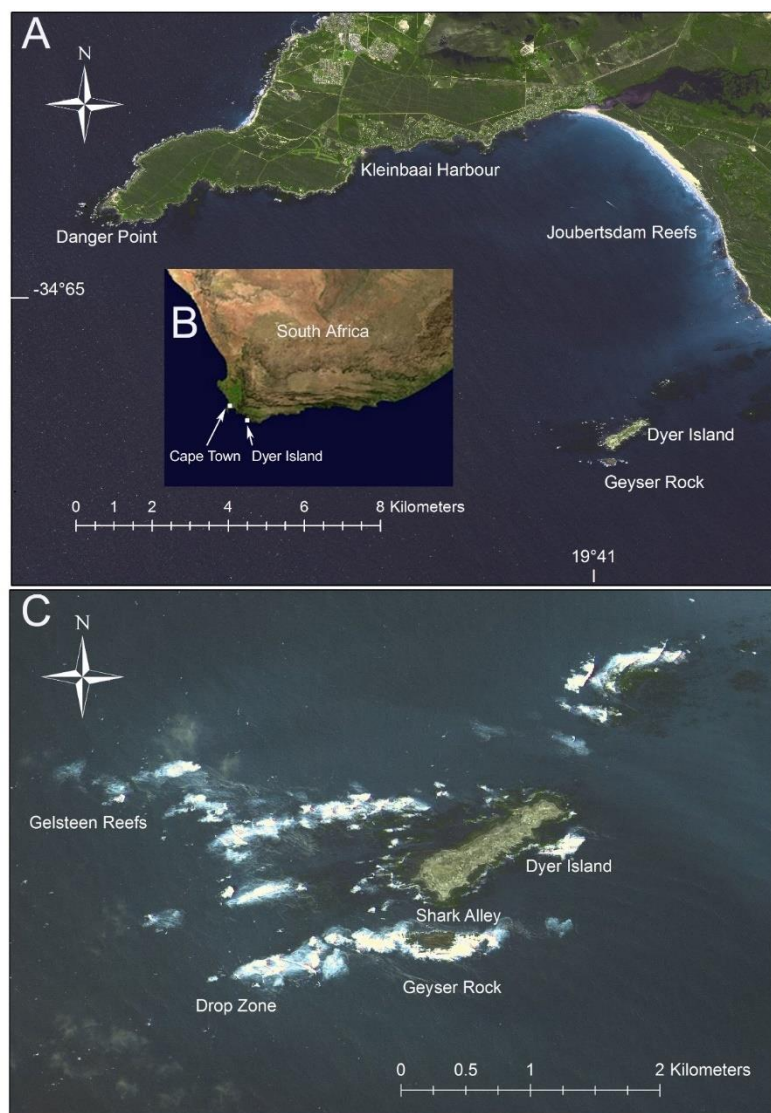
**Supplementary Material**

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## Additional Methods

### Study Site

White sharks were tagged at Dyer Island and Geyser Rock, within the Gansbaai Shark Cage Diving Area (Figure S3), using the same locations, research vessel and attracting methods as Jewell et al. [1].



*Figure S3: Study site within the Gansbaai Shark Cage Dive Area. All sharks were tagged within the vicinity of Dyer Island and Geyser Rock (C) off the Western Cape coastline of South Africa, in the southeastern Atlantic Ocean. Figure from Jewell [2].*

## White Shark Tagging

We used *Customized Animal Tracking Solutions (CATS)* CATS-Cam, CATS-Diary and *Monterey Bay Aquarium Research Institute (MBARI)* CaféCam high-resolution biologgers. All CATS biologgers contained triaxial accelerometers, gyroscopes and magnetometers set to record at 40 Hz, plus depth, temperature and light sensors. Tagging methods and CATS-Cam/Diary specifications are the same as used in Chapple et al. [3], CaféCam units used high-resolution video and were paired with CATS-Diary units for comparison to CATS-Cam and attached to sharks using the same methods.

## Data Analysis

### Video Processing: Solomon Coder

We categorised habitat use and prey encounters by uploading AVED videos into Solomon Coder (Version beta 17.93.22, see Mirko et al. [4]), recording all observations of anchored kelp. ‘High’ density kelp forest was assigned when kelp filled equal to or more than 50% of the available field of view from the camera (after accounting for field of view taken up by the sharks head), whereas ‘low’ was assigned when some, but less than 50% of the field was filled. Cape fur seals, other potential prey and conspecifics were also recorded, as were interactions with cage diving vessels, rock and reef habitat features, off-centre swimming orientations, high to moderate or low visibility and observations on body movements, such as active bursts or gapes (Figure S4). Observations were recorded by selecting customised and predetermined ‘buttons’ on the coder, that were either ‘durations’ (that were turned on at the beginning of the observation and then off at the end i.e. when kelp enters the frame of view and then moves out of view) or ‘events’ (instant observations that are recorded once in the coding sheet i.e. when a breach occurs). Once a video was run through the coder, the results were exported to excel, where durations, percentages and occurrence of each button selection were summarised.

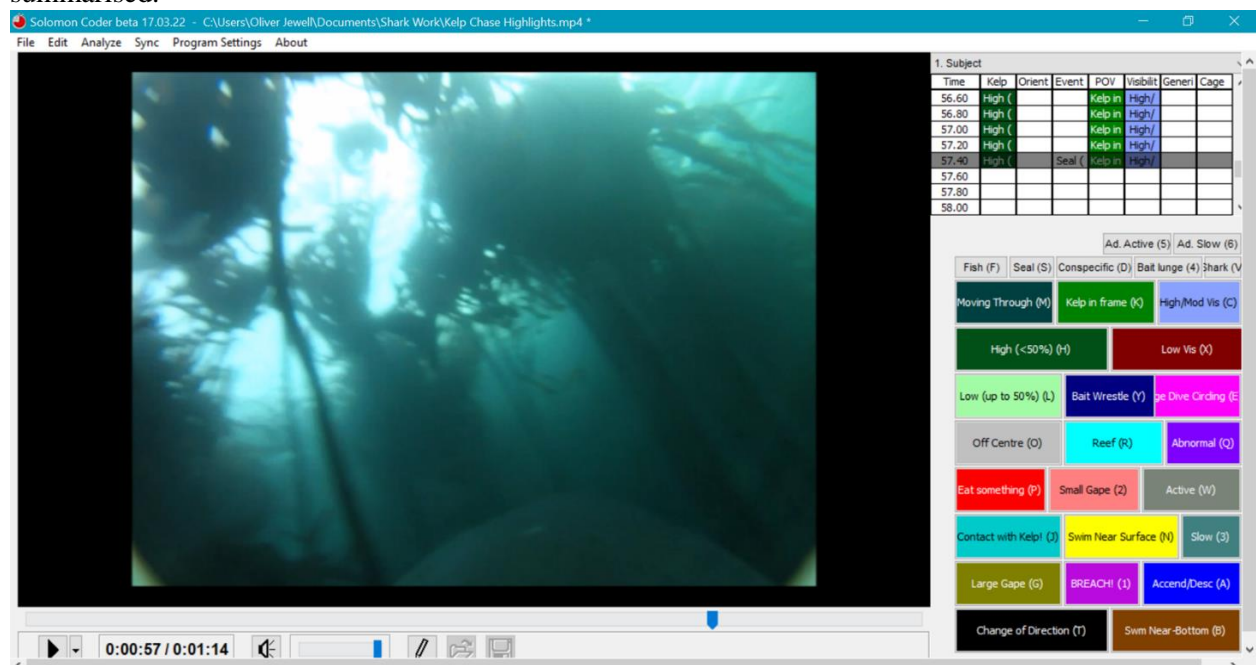


Figure S4: Solomon Coder (version beta 17.03.22) config was used to analyse AVED footage in real-time and categorise habitat and presence of kelp as well as other observations. In the example image, Shark 5 encounters three seals within high-density kelp.

### Logger Processing: Pseudo-Track, ODBA and Heading

We exported log data from CATS-Cam and Diary units to Igor Pro 7 (*Wavemetrics*) with the Ethographer package (Version 2.04 *University of Tokyo*), clipping tracks to on-shark recordings by observing depth and X-axis acceleration data to find moments of attachment and release of fin-clamp to the shark. We then looked for moments that could match video data to log data (neither model of AVED included time stamps on video or log). We used depth, raw acceleration, light and dynamic sway (tail beats) to do this. This was easiest in videos that included AVED attachment and videos that ran consecutively and hardest if the camera was not recording when deployed, filming cycles were duty cycled (i.e. programmed to film at certain times of the day only) or had delays in between video recordings. In the remaining unmatched videos, tail beats and glides between climbs to the surface and dives to depth [5], dynamic events such as kelp striking the camera unit, or lunges at bait-lines while interacting with cage diving vessels were used to match videos to logs to the nearest second. Matching points between videos and logs were then cross-referenced between events to check for and correct any time/sensor drift.

Framework4 (*Swansea University*) [6] was used to reconstruct pseudo-tracks of tagged sharks. Unfortunately, the log of Shark 8 that included a large amount of kelp forest interaction, was lost and could not be processed and the log of Shark 2 that included kelp forest interaction in low visibility suffered data corruption for the entire section of the log the camera was recording. The CATS diary paired with CaféCam deployments included a magnetic paddle wheel for speed sensor calibrations, distorting the magnetometer sensor and preventing the calculation of pseudo-tracks for these deployments. Two additional deployments ended early when sharks interacted with cage diving boats, while two other attachments were placed with poor field of view of the camera. The data from these deployments were not included in the results.

Acceleration and magnetometer data were used to create head yaw angles and pseudo-tracks in the Dead Reckoning Wizard of Framework4 [6, 7]. We selected a 3-second smoothing window (120 data points) to calculate pitch and roll, a constant speed assumption of 0.8 m/s (*sensu* Andrzejaczek et al. [7]) with the GPS recording of tagging location used as a start point. The previews of mapped tracks were used to confirm correct sensor alignment and give an impression of the movement of the sharks after tagging. There was no further georeferencing of the tracks and no accounting for the effect of currents or on changes in the speed, as such the tracks may appear different in shape and length to the actual movements made by the animals while tags were attached [7]. Once pseudo tracks were calculated, yaw angle, pseudo latitude and longitude data fields were exported.

Head yaw angle was used to calculate turning angles using the same techniques as Andrzejaczek et al. [7]. Head yaw was smoothed using a 3-second box smoother to remove the effect of regular tail beats on yaw before all data was resampled to one-second intervals using a Hanning Low Pass Filter and converted to a 0-360° scale. Overall Dynamic Body Acceleration (ODBA) was calculated in Igor Pro using the Ethographer package by deriving static acceleration from raw accelerometer data using a 3-second box smoother, subtracting static acceleration from raw to give dynamic acceleration and then summing the absolute dynamic accelerations from each of the three axes [5, 7, 8]. ODBA was then smoothed to one-second intervals using a Hanning Low Pass Filter. Datasets were then exported for statistical analysis with the factor headings Local\_Time, Kelp (value of 1 or 0), ODBA, Turning\_Angle and Shark\_ID at one-second (1 Hz) values. To avoid any effects of baiting, periods of interaction with cage diving operators or our research vessel were removed.

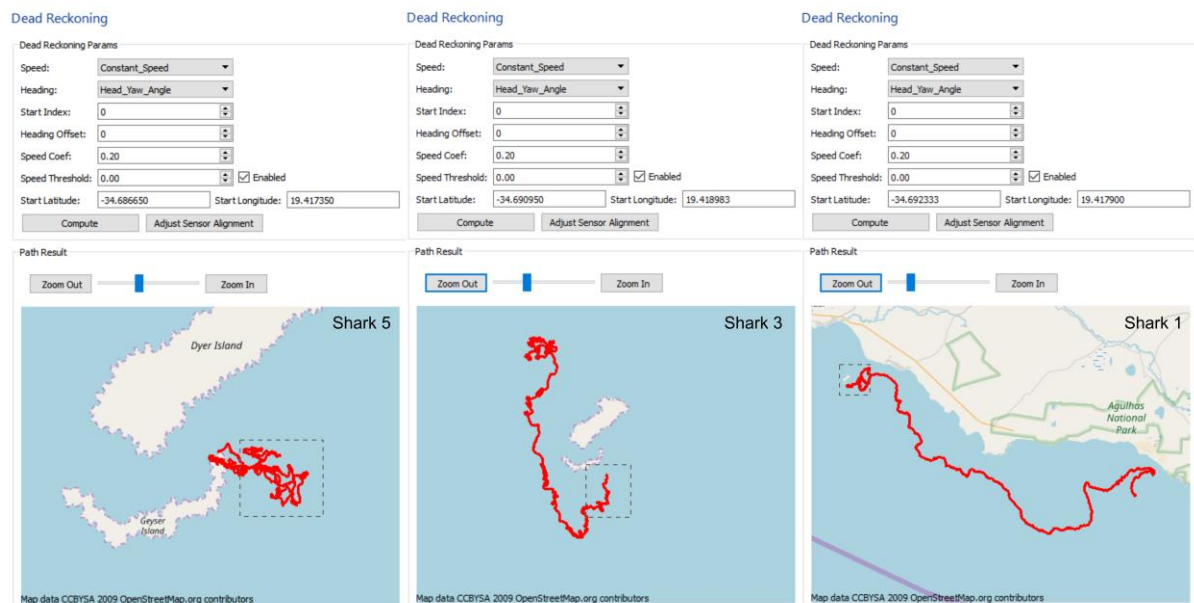
### Randomisation Analysis

The Randomisation Analysis and subsequent testing was performed in R (*R Core Team* [9]) Bootstrap replication with replacement was used to sample 1000 independent datasets for each individual,

ensuring adequate accounting for autocorrelation by sampling 1 Hz estimates at intervals larger than 30s (as determined across individuals by ACF plots). Sampling was structured proportionally based on the amount of habitat use (see Table 2), resulting in each replicate having an overall sample size of 216 (3 inside kelp, 213 outside), 205 (30 inside, 175 outside), 457 (127 inside, 330 outside), and 149 (100 inside, 49 outside) for sharks 1, 3, 4, and 5 respectively. For each replicate, behavioural differences were tested with a Kruskal-Wallis rank sum test and a Dunn post-hoc test. Statistics are summarised as the percent of replicates that reach significance below  $\alpha = 0.05$ , the median and 95%ile of observed Kruskal-Wallis statistics, and the median and 95%ile of observed mean rank differences in the Dunn Test. For ODBA, estimates are scaled between 0 and 1 for each individual shark. For turning angles, estimates are smoothed evenly over 10s to account for zero inflation and then scaled between 0 and 1 for each individual shark.

## Additional Results

The pseudo-tracks appear to suggest that one animal moved away from the island system, with Shark 1 moving along the coast towards Cape Agulhas and the Indian Ocean (Figure S5). This tag was found on a beach in Struisbaai the following day and confirms the shark did indeed leave the system. Shark 3 moved into deeper water away from the island before returning the following day. Shark 5 appeared to remain close to the island system until the tag was removed by thick kelp. The other sharks without pseudo-tracks appeared to remain close to the island system as several recordings of sharks at cage diving vessels during their deployments were recorded, and most tag recoveries occurred close to the island system.



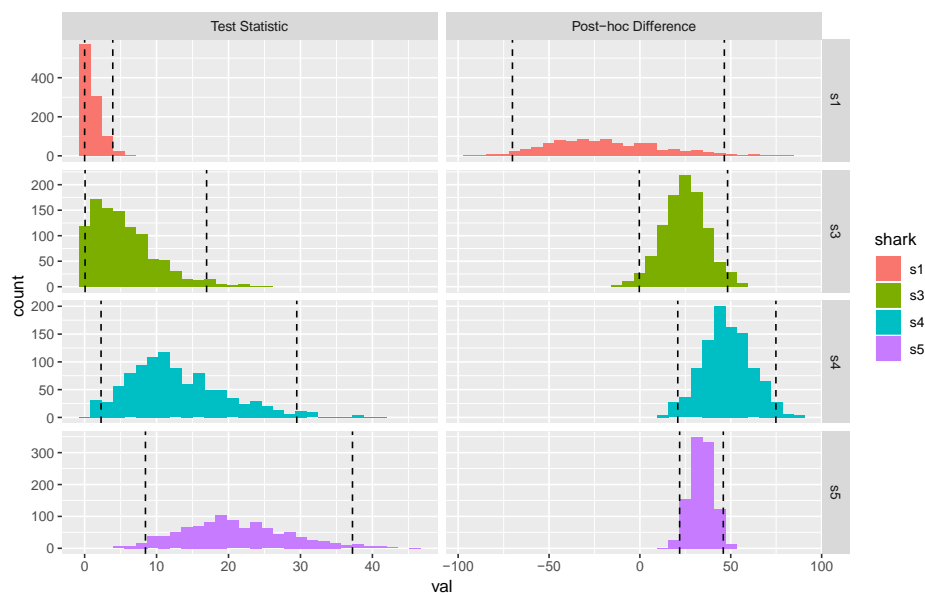
*Figure S5: Triaxial accelerometer and magnetometer data could be matched to video footage from three shark deployments, the raw pseudo tracks revealed Sharks 2 and 5 remained within the island system while Shark 1 swam towards Cape Agulhas and the Indian Ocean. Grey boxes represent areas with matching video footage.*

Pseudo-tracks and data logs could only be analysed if matched to video and subsequent kelp observation status; this was only possible for four shark deployments with ODBA and three with ODBA and turning angles. Of these, Shark 5's deployment had the largest duration and percentage of time within kelp forest (Figure S2A). Following the end of the matched video, shorter video clips revealed this shark continued to swim through dense kelp forest until the AVED became entangled in and was removed from the shark by a kelp frond. This footage can be seen in the Supplementary

Video. Shark 3 was tagged late in the afternoon after the AVED had been recording for a number of hours and using up the majority of its data storage. This meant only 1.8 hrs of footage was recorded while attached to the shark, although it could all be matched to log (Figure S2B). Shark 1 had the lowest of all kelp observations and was the only shark not to encounter dense kelp forest. It did so with a high level of activity and low turning angles as it moved away from the Dyer Island Reserve and towards the Indian Ocean (Figure S2C).

## Statistical Analysis

Comparing bootstrapped subsamples of metrics observed inside and outside kelp for 1000 permutations, we compile significant differences observed through nonparametric statistics as the proportion of permutations below the alpha cut-off (0.05). Figures S6 and S7 report the distribution of test statistics (Kruskal-Wallis H) and rank difference (Dunn test) for all bootstrap permutations across all individuals for ODBA and turning rates. Dashed bars depict a 95%ile of the distribution, whereby deviations from zero indicate a high proportion of the data observed inside kelp is statistically distinct from data observed outside kelp. Subsamples of data from habitat classes was sampled proportionally to ensure equivalent representation as the underlying data, while still accounting for autocorrelation processes.



*Figure S6: Bootstrap distributions of Kruskal-Wallis tests and the mean rank difference determined by the Dunn post-hoc test for observed ODBA estimates inside and outside kelp habitats.*

Rank differences for ODBA observed in Shark 4 and 5 wholly deviated from zero, indicating ODBA metrics were always higher inside of kelp than outside. Confirming this, more than 95% of permutation trials exhibited significant differences (Table 2) underlying the results robustness. Differences in ODBA between habitat classes for Shark 3 were more marginally significant, as the rank differences overlap zero (indicating some overlap in distributions between inside and outside kelp) and ~50% of replicates show significance. The broad distributions of Shark 1 show the absent effect for this animal, that rarely used kelp and largely travelled out of the study area.

Differences in turning rate were not as stark as ODBA, yet in two individuals (Shark 3 and Shark 5) 70% of bootstrap replicates were observed to have greater turning rates in the presence of kelp than



otherwise. Tight confidence percentiles (95% dashed bars) in Shark 3 and 5 depict a commonly larger turning angles inside of kelp, while the broad distribution of rank differences in Shark 1 exhibit a more random underlying process (Figure S7).

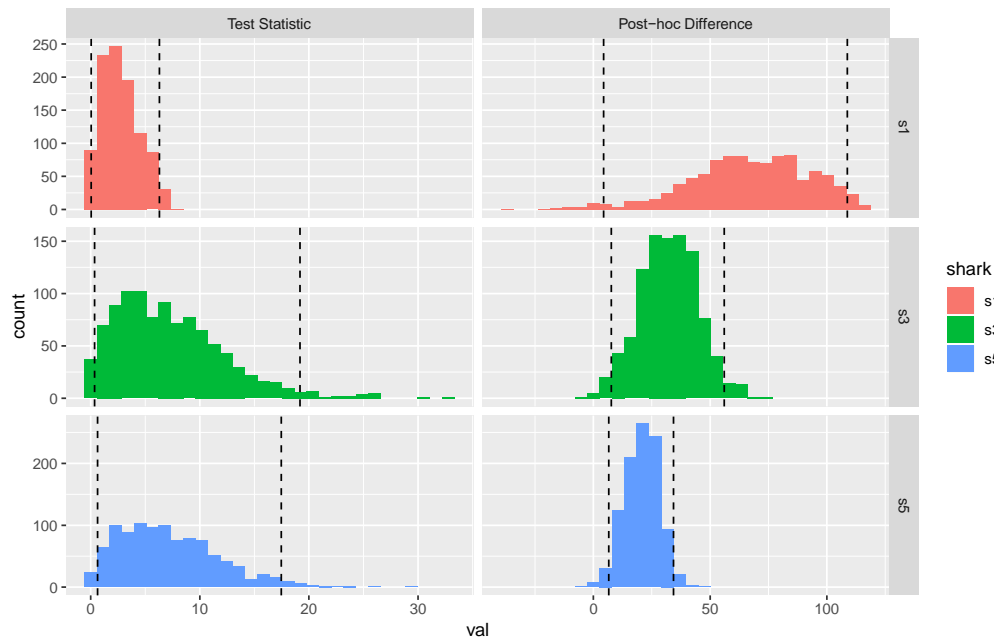


Figure S7: Bootstrap distributions of Kruskal-Wallis test statistics (left) and mean rank differences determined by the Dunn post-hoc test (right) for observed relative turning angles inside and outside kelp habitats.

## Weblinks

Ethographer: <https://sites.google.com/site/ethographer/download>

Framework4: <http://framework4.swansea.ac.uk/software.php>

Igor: <https://www.wavemetrics.com/>

R: <https://www.r-project.org/>

Solomon Coder: <https://solomoncoder.com/>

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