Core habitat use of an apex predator in a complex marine landscape

Oliver J. D. Jewell[1,2,*], **Michelle A. Wcisel**[1,3], **Alison V. Towner**[1,3], **Wilfred Chivell**[1], **Lize van der Merwe**[4,5], **Marthán N. Bester**[2]

[1]**Dyer Island Conservation Trust, Geelbek St, Kleinbaai, PO Box 72, Gansbaai, 7220, South Africa**

[2]**University of Pretoria, Mammal Research Institute, Department of Zoology & Entomology, Private Bag X20, Hatfield, Pretoria, South Africa**

[3]**University of Cape Town, Department of Zoology, Rondebosch 7701, South Africa**

[4]**Division of Molecular Biology and Human Genetics, Faculty of Medicine and Health Sciences, Stellenbosch University, Tygerberg, South Africa**

[5]**Department of Statistics, University of the Western Cape, Bellville, South Africa**

*Corresponding author: oliverjewell@gmail.com

Supplement.

Tagging and tracking protocol

We attracted sharks to the research vessel for tagging using standard chumming procedure. Waste teleost products were diluted into seawater and a chum slick was formed; this can attract sharks downstream of the vessel from as far as 1 to 2 km away, although generally areas are chosen that sharks are already making use of (i.e. close to a seal colony, adjacent a reef system). They were attracted to the stern of the vessel using a fish-head bait, which they were not allowed to consume. We approximated shark total length (TL) as sharks circled the research vessel; often several passes were made before the shark came close enough to tag externally with a tagging pole (Fig. S1). Further calibrations of size estimates could be made if the shark was seen from Marine Dynamics Tours shark cage diving vessel; three of the sharks were observed during the tracking period and a fourth the following year. Photos were taken from above as the sharks moved close to cage of known dimensions and basic photogrammetry estimates made using Photoshop (similar to Jewell & Wcisel 2012). Age class of individuals was determined through body (TL) and clasper size; using Estrada et al. 2006 as a guide; Shark 1 was identified as female and subadult (320 cm), Shark 2 and Shark 5 were both identified as adult males (>400 cm) and Shark 3 and Shark 4 as sub-adult (350 and 300 cm respectively).

Fig. S1. Sharks were tagged externally while free-swimming with the use of a pole spear after being attracted with bait and chum. Photo credit: Dawn Watson, Dyer Island Conservation Trust

We followed a tracking protocol similar to the methods of Johnson et al. (2009) and Jewell et al. (2012). We collected data automatically from the VR100 with each 'ping' received (later filtered to 5 min positions) and by hand every 5 min. Sharks were tracked at a minimum distance of 20 to 40 m to avoid interfering with natural movements (Johnson et al. 2009). If the tracking vessel got closer, sharks would occasionally move towards the vessel to investigate it; this was therefore avoided as much as possible. If position 'pings' exceeded 80 dB, boat engines were cut to limit any distraction. Positions can be corrected from the tracking vessel's location to the shark's location in the water column if the directions of the shark's movements are recorded and distance of tags-to-signal strength received at different gain settings are calibrated before tracking (Heithaus et al. 2002). However, the equipment failure in the VR100 resulted in the loss of archived data for two of the sharks tracked. As a result, signal strength/gain data for these sharks was not available and we were not able to correct positioning of these sharks. Comparing corrected position data to uncorrected position data from the same tracks provided non-significant differences for Rate of Movement (ROM), Linearity Index (LI) and Minimum Convex Polygon (MCP) calculations; distance to Geyser Rock would have lower values as sharks were able to approach the island closer than the research vessel (Jewell 2013). However, the mean distance from Geyser Rock was 318 m during daylight, compared to 1267 m during the night and it is unlikely that correcting would have affected the significance of the difference between the two (Jewell 2013). To compare the effect of light levels during daytime, night, dawn and dusk, we used Johnson et al.'s (2009) definitions: daytime – any position recorded during daylight hours, night – any position recorded during the night, dawn/dusk – any position recorded half an hour before or after dusk (Figs. S2 & S3).
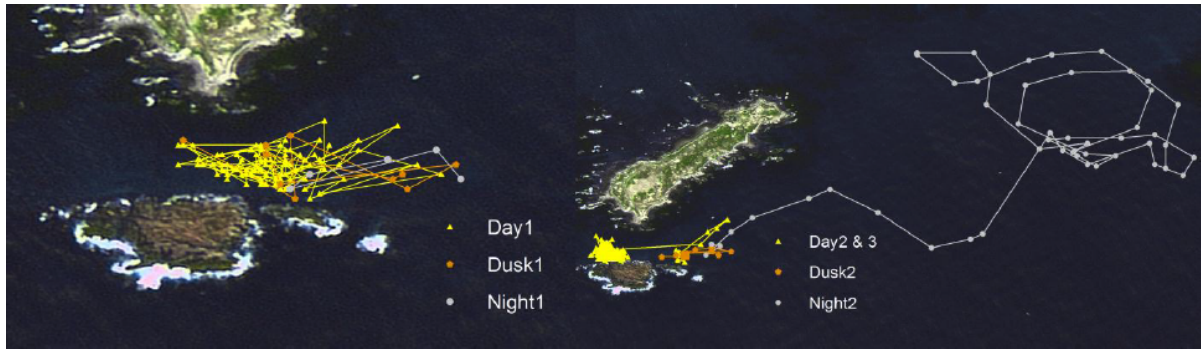
Fig. S2. Example of day and night tracking of Shark 2 an adult male, which included daytime movements in Shark Alley followed by a night migration to a distant reef. Tracking was abated in the early hours before being restarted in the morning. During this time, the shark had returned to Shark Ally where it remained for the duration of daytime tracking
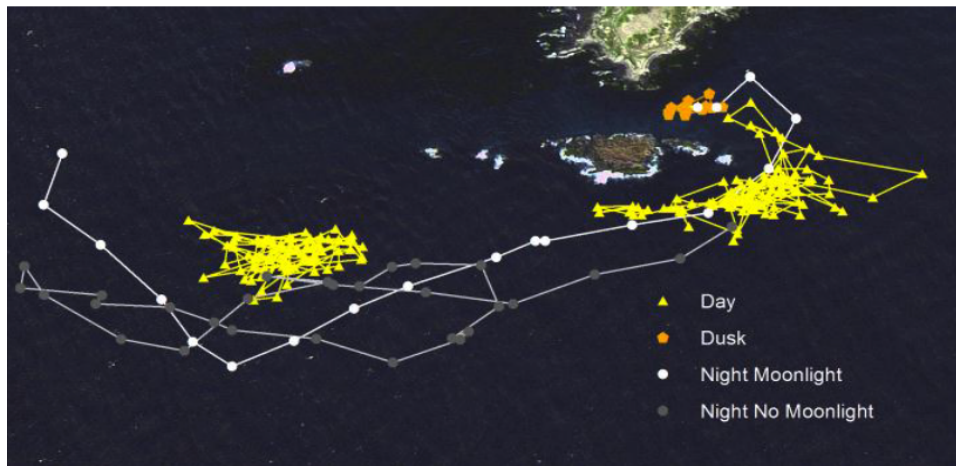

Fig. S3. Three non-continuous tracks of Shark 5, an adult male, which was found in 2 distinct areas during daytime tracking: off of the shallow peninsular to the west of the Geyser Rock system at the Drop Zone and off of the SE corner of Geyser Rock and in the mouth of Shark Alley. During dusk, the shark was also tracked in the mouth of Shark Alley before larger-scale back and forth movements were made under moonlight south of the Geyser Rock system; following moonset these movements continued a short time before conditions worsened and tracking was halted

GIS analysis

Rate of Movement

Spatial data was analysed using ArcMap 10 and the Animal Movement extension of ArcView 3.2. ROM, in meters per second (m s^{-1}), was determined by calculating the distance between consecutive positions and dividing by time elapsed (Strong et al. 1992, Johnson et al. 2009). These calculations are used to give an estimate relative activity over periods of time, but this cannot be considered a measurement of swimming speed because it does not incorporate error, vertical changes or currents, and assumes that the movement has been in a straight line from point to point

(Sundström et al. 2001). Accelerometers (as in Gleiss et al. 2013) were not available in this study.

Swimming linearity

Linearity of sharks' individual tracks was determined using the LI of Bell & Kramer (1979) and used by Sundström et al. (2001), Johnson et al. (2009) and Jewell et al. (2012):

$$LI = (Fn - F1)/D$$

where Fn − F1 is the distance between first and third position taken for the shark and D is the total distance travelled by the shark. A linearity of 1 indicates linear movement (i.e. straight line travel). A LI near zero indicates little movement from the area with a great deal of overlap and reuse of the activity space. Johnson et al. (2009) defined high levels of ROM and LI as 'travelling', low levels of ROM and LI as 'resting' or 'patrolling' and high levels of ROM with low levels of LI close to the seal colony in Mossel Bay as 'hunting'.

Distance from Geyser Rock

Swimming distance from the seal colony was used to asses if certain times of the day are more devoted to foraging on seals than others. The distance was measured from position (at 5 min intervals) to the nearest point of Geyser Rock using the measuring tool from ArcMap 10. Seals use the shallow ridge and kelp to the east of Geyser Rock as a refuge (M. Wcisel, A. de Vos & J. O'Riain unpubl. data), as such the kelp ridge was included as an extension of Geyser Rock. Similarly, the thick areas of kelp at the Geldsteen reefs were also included as an extension of refuge.

Home range analysis

Activity area was determined from MCP. MCPs calculate an area from the outermost positions of a track, creating a range which encompasses all areas of movement and areas in between (Jewell et al. 2012). Discovery curves were derived total activity area over time from every cumulative hour of movement (i.e. 0–1, 0–2, 0–3 etc.) for each shark (as in Goldman & Anderson 1999), with a new day's tracking starting as the next hour of cumulative tracking. Daily activity areas were determined through individual tracks. Overlap in daily activity areas of the same individual were calculated using an Index of Reuse (IOR; as in Jewell et al. 2012). Traditional location-based kernel estimates were calculated with the animal movement tool on Arc 3.2 with smoothing parameter calculated using Least Squares Cross Validation (LSCV) (as in Jewell et al. 2012). Utilisation Distribution (UD) values were recorded from the 95% (outer 95% concentration of habitat use) and 50% (inner 50% core area of habitat use) isobars. Next, the Pascal programme described in Benhamou & Cornélis (2010), Benhamou (2011) and Benhamou & Riotte-Lambert (2012) was used to compute Movement-based Kernel Density Estimate (MKDE) UDs. We first computed a diffusion coefficient (D) of roughly 1000 for each shark using the Biased Random Bridges (BRB) method in the programme (Benhamou 2011). H_{min} (minimum smoothing parameter in meters) was set to 100 (as in Cornélis et al. 2011) and L_{min} to 10 (the length threshold of movement in meters, i.e. any movement of less than this is

considered to be resting). This is less than previous studies (Cornélis et al. 2011 set L_{min} of around 50 m) as the location data in this study was sampled at shorter time intervals and resting in sharks is difficult to define. Johnson et al. (2009) defined limited movements of actively tracked white sharks in Mossel Bay as resting; however, we observed white sharks in this study site making very limited movements whilst predating on Cape fur seals, particularly in Shark Alley. Without the use of shark-borne camera equipment and accelerometers to gain a better understanding of these periods of low-activity/limited movement, we preferred to use a lower L_{min} value. When the boundaries of Dyer Island and Geyser Rock were added into the equation, the programme began to stall due to the minimum requirements of boundary lengths within the programme (boundary length cannot be in excess of $3 \times H_{min}$, in this case, 300 m, and angles between segments must not be sharper than 90°). This is an improvement on the original programme settings (S. Benhamou pers. comm.), yet still not of fine enough resolution to incorporate the boundary lines of Geyser Rock. As a result, we used a lower H_{min} value of 50 giving boundary constraints of 150 m, enough to incorporate the boundary lines of Geyser Rock and the kelp ridge to its west without excluding any tracked movements. A second boundary was at Dyer Island and a third would have been used along the coastline had a shark's UD extended over it. Once MKDEs were projected, they were imported into Arc GIS 10 for display and spatial analysis. Areas were calculated from the 95% and 50% isobars.

LITERATURE CITED

Bell WJ, Kramer E (1979) Search and anemotactic orientation of cockroaches. J Insect Physiol 25:631–240

Benhamou S (2011) Dynamic approach to space and habitat use based on biased random bridges. PLoS ONE 6:e14592

Benhamou S, Cornélis D (2010) Incorporating movement behavior and barriers to improve kernel home range space use estimates. J Wildl Manag 74:1353–1360

Benhamou S, Riotte-Lambert L (2012) Beyond the Utilization Distribution: identifying home range areas that are intensively exploited or repeatedly visited. Ecol Modell 227:112–116

Cornélis D, Benhamou S, Janeau G, Morellet N, Ouedraogo M, de Visscher MN (2011) Spatiotemporal dynamics of forage and water resources shape space use of West African Savanna buffalo. J Mammal 92:1287–1297

Estrada JA, Rice AN, Natanson LJ, Skomal GB (2006) Use of isotopic analysis of vertebrae in reconstructing ontogenetic feeding ecology in white sharks. Ecology 87:829–834

Gleiss AC, Wright S, Liebsch N, Wilson RP, Norman B (2013) Contrasting diel patterns in vertical movement and locomotor activity of whale sharks at Ningaloo Reef. Mar Biol 160:2981–2992

Goldman KJ, Anderson SD (1999) Space utilization and swimming depth of white shark *(Carcharodon carcharias)* at the South Farallon Islands, central California. Environ Biol Fishes 56: 351–364

Heithaus MR, Dill LM, Marshall GJ, Buhleire B (2002) Habitat use and foraging behavior of tiger sharks (*Galeocerdo cuvier*) in a seagrass ecosystem. Mar Biol 140:237–248

Jewell OJD (2013) Foraging ecology of white sharks *Carcharodon carcharias* at Dyer Island, South Africa. MSc thesis, University of Pretoria

Jewell OJD, Wcisel MA (2012) A leatherback turtle stranding at Danger Point, Gansbaai, South Africa. S Afr J Wildl Res 42:147–150

Jewell OJD, Johnson RL, Gennari E, Bester M (2012) Fine scale movement patterns and activity areas of white sharks (*Carcharodon carcharias*) at Mossel Bay, South Africa. Environ Biol Fishes 96:881–894

Johnson R, Bester MN, Dudley SFJ, Oosthuizen WH, Meÿer M, Hancke L, Gennari E (2009) Coastal swimming patterns of white sharks (*Carcharodon carcharias*) at Mossel Bay, South Africa. Environ Biol Fishes 85:189–200

Strong WR, Murphy RC, Bruce BD, Nelson DR (1992) Movements and associated observations of bait-attracted white sharks *Carcharodon carcharias*: a preliminary report. Aust J Mar Freshwater Res 43:13–20

Sundström LF, Gruber SH, Clermont SM, Correia JPS, de Marignac JRC (2001) Review of elasmobranch behavioural studies using ultrasonic telemetry with special reference to the lemon shark, *Negaprion brevirostris*, around Bimini Islands, Bahamas. Environ Biol Fishes 60:225–250