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BRIEF COMMUNICATION

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Back to the wild: movements of a juvenile tiger shark released from a public aquarium

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Abstract

Sharks are an important attraction for aquaria; however, larger species can rarely be kept indefinitely. To date, there has been little work tracking shark movements post-release to the wild. The authors used high-resolution biologgers to monitor a sub-adult tiger shark's pre- and post-release fine-scale movements following 2 years of captivity in an aquarium. They also compared its movement with that of a wild shark tagged nearby. Despite the differences in movement between the two sharks, with vertical oscillations notably absent and greater levels of turning seen from the released shark, the captive shark survived the release. These biologgers improve insight into post-release movements of captive sharks.

KEYWORDS
biologging, captivity, fine-scale telemetry, *Galeocerdo cuvier*, Shark Bay, Western Australia

The benefit of aquarium-based public outreach and educational programmes to long-term marine conservation is well established (Falk *et al*., 2007). Sharks are an important attraction for aquaria, and as they belong to some of the most misunderstood and threatened orders on the planet, housing them also has great educational value (Dulvy *et al*., 2021; Grassmann *et al*., 2017). However, sharks held in aquaria are normally caught from wild stocks, and larger species cannot be kept indefinitely because of their size and pelagic life cycles (Buckley *et al*., 2018; Smale *et al*., 2012). Releasing animals into the wild raises ethical concerns associated with deciding when and where the release should take place, and whether the animals will survive in the wild post-release. There are high-profile examples of marine animals that have died post-release {*e.g*., Helvarg, 2016 [a Californian seal lion *Zalophus californianus* (Lesson, 1828) that was eaten by a shark moments after release]; Miskelly *et al*., 2012 [a king penguin *Aptenodytes patagonicus* (Miller 1778) that only survived for days after release]}, yet literature on the outcomes for sharks released to the wild is scarce, with only a few case studies available (Buckley *et al*., 2020; Lee *et al*., 2015; Marin-Osorno *et al*., 2017; Smale *et al*., 2012; Van Dykhuizen *et al*., 1998; Weng *et al*., 2012). For sharks, of particular concern are stress-related deaths, which are common during release procedures, or capture in commercial fisheries,

FIGURE 1 (a) The main display area of Ocean Park Aquarium where the captive tiger shark was housed for over 2 years. (b). The captive tiger shark with a CamTag in place while swimming in captivity pre-release to the wild. (c). Still from post-release video obtained from the CamTag while the shark is freely swimming in the wild

which have been documented during the weeks and months after release (Marin-Osorno *et al*., 2017; Weng *et al*., 2012). Most studies investigating movements of sharks post-release from aquaria have used passive acoustic telemetry which is useful to determine space use and residency times within the range of an array of listening stations or links between monitored areas (Buckley *et al*., 2020; Lee *et al*., 2015), or archival tags, which provide information on the shark's migration and dive patterns post-release (Marin-Osorno *et al*., 2017; Smale *et al*., 2012; Weng *et al*., 2012). Yet there has been little consideration of the adjustments to swimming and movement patterns released sharks must make to survive in the wild, and there has been little use of high-resolution biologgers (also referred to as smart tags) that can record such fine-scale movements during the release of captive sharks (but see Nakamura *et al*., 2020), despite their extensive use to monitor the movements of wild populations (Andrzejaczek *et al*., 2019; Gleiss *et al*., 2017; Jewell *et al*., 2019; Papastamatiou *et al*., 2022).

Here, the authors describe the fine-scale movements of a 2.2 m total length (TL) male tiger shark *Galeocerdo cuvier* (Peron & Lesueur 1822) that was released to the wild after 2 years in captivity at the Ocean Park Aquarium in the Shark Bay World Heritage Area, Western Australia. The shark was tagged inside the main display area of Ocean Park Aquarium to record the movements of the tiger shark while captive ('Captive Aquarium') at 09.50 hours on 5 August 2022. The display is an approximately 1.8 million l circular pool with a maximum depth of 3 m (Figure 1a,b). The tiger shark was tagged using a Customized Animal Tracking Solutions, Australia (CATS) camera biologger (CATS Shark Cam generation 10, henceforth CamTag for brevity) fit to a stainless-steel clamp with a galvanic timed release and containing a corrodible arm (Chapple *et al*., 2015). The CamTag records video at predetermined duty-cycled intervals to conserve battery and memory. In contrast, internal sensors constantly record triaxial accelerometer, gyroscope, magnetometer, depth, temperature and light at 50 Hz sampling intervals. The CamTag also contains a Wildlife Computers, California, SPOT tag and an Advanced Telemetry System, Minnesota (ATS), VHF tag that activate upon release and are used to help retrieve it. Deployment of the CamTag on the captive shark occurred during a feeding event while the shark was freely swimming, using a pole with a spring-trigger release in similar methods to those described in Chapple *et al*. (2015). The CamTag was detached from the tiger shark at 20.00 hours on the same day after recording 10 h and 10 min of data. Once detached, the CamTag floated to the side of the aquarium and was picked up the following morning for data downloading.

The captive tiger shark was caught for release by aquarium staff at 17.15 hours on 23 August 2022, 2 years and 34 days after its initial capture. The husbandry team attracted the shark with bait then used a tail rope to secure it, placed it into a stretcher and took it to the nearby beach (*c*. 100 m). Once the shark was in the water, its TL (m) was measured using a tape, and an identification marker tag was placed nearer the fin tip. The CamTag was placed at the base of the shark's first dorsal fin to record its movements post-release ('Captive Post-Release'). The entire process took less than 10 min, and the shark was released at 17.24 hours. The CamTag was detached from the shark at 17.00 hours the following day, on 24 August 2022, after logging 23 h and 36 min of fine-scale movement data and 5 h of video footage (Figure 1c). The unit was retrieved from the sea the following morning using a combination of SPOT and VHF transmissions, and the data were subsequently downloaded.

To compare this shark's movement to a shark not kept in captivity, the authors also caught, tagged and released a wild 2.8 m female tiger shark at Big Lagoon (Figure 2a), located *c*. 25 km north of Ocean Park Aquarium ('Wild Shark'). The wild shark was caught by a scientific drumline at 13.00 hours on 5 April 2022, measured, tagged with the same CamTag described earlier and released following similar methods to Heithaus *et al*. (2002). The CamTag was detached from the wild shark at 06.00 hours the next morning during a sudden period of fast swimming (burst event), after recording 17 h and 18 min of data. The CamTag was picked up by a local commercial beam trawler and subsequently returned to the authors for data download.

To extract information on multiple movement characteristics of the sharks, the authors processed tag data from each deployment using the Ethographer package (version2.04) in Igor Pro 9 (Sakamoto *et al*., 2009), Framework4 (version 2.5.0; Walker *et al*., 2015) and the

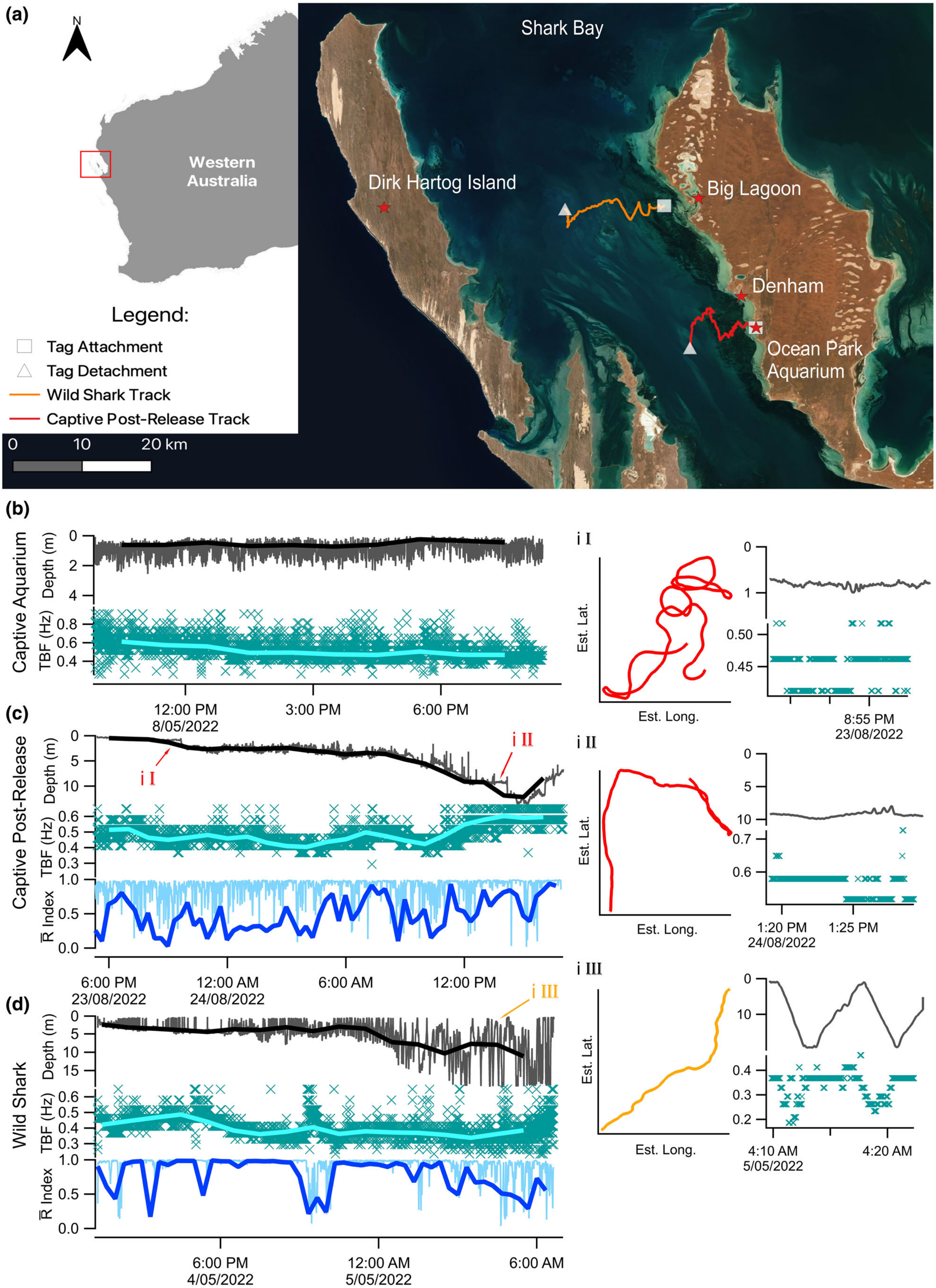

FIGURE 2 Legend on next page.

circular package (version 0.4–95) in R (version 4.1.0; Lund & Agostinelli, 2017; R Core Team, 2021). To examine shark activity, they calculated dynamic acceleration using vectorial body acceleration (VeDBA), which is calculated in *g* from all three axes of accelerometer data (Qasem *et al*., 2012), and tail beat frequencies (TBF), which were calculated in Hz using a fast Fourier transform from oscillations in the lateral rotation of the dorso-ventral axis of the gyroscope (Noda *et al*., 2014). They used VeDBA to determine when burst events had occurred (acceleration >1 *g*) and TBF to observe if activity increased or decreased throughout the day (Jewell, 2022). To examine vertical shark movements through the water column, they used pressure sensor data to determine depth use in meters and how this changes in time using vertical velocities in metres per second (Andrzejaczek *et al*., 2019). They also created an estimated movement path (deduced-reckoned) based on rates of three-dimensional acceleration and heading (magnetometer) data (Jewell *et al*., 2019). From this path, they examined potential horizontal search patterns by indexing turning rates ($\bar{R}$ Index, where one is equal to straight swimming and 0 indicates high tortuosity) calculated from heading data at 1- and 20 min intervals (Jewell *et al*., 2023; Lund & Agostinelli, 2017). Turning angle and heading estimates could not be calculated from pre-release tracking within the aquarium because a magnet had been used to disable the VHF transmitter.

While in the aquarium, the captive tiger shark displayed uniform levels of activity (0.51 ± 0.10 Hz TBF) and depth use (0.94 ± 0.46 m) throughout most of the 10 h of recording, except for a slight elevation in activity within the first 2 h of deployment, possibly due to adjustments to the extra drag caused by the deployed tag (*i.e*., van der Hoop *et al*., 2014; Figure 2b). Several tight turns were observed in the footage from the camera tag, but no major bursting events were recorded, and no further feeding events took place during the rest of the deployment. Interestingly, the captive shark displayed the largest vertical velocity while inside the aquarium (Supporting Information Table S1), despite having the most limited depth range (max 3 m). This high velocity may be an artefact of the shallow environment inside the aquarium, resulting in oscillations captured at faster rates by the unit, as this was not seen in the post-release data for the same shark. The shark was released into knee-deep water (*c*. 50 cm in depth) and remained in shallow water (<1 m depth) for the first 4 h outside of the aquarium (Figure 2c). During this period, track estimation showed repeated movements along the edge of a sand flat (Figure 2i I), whereas video footage of the first 2 h of the release confirms the shark was swimming just off the sea floor. Once the shark left this area, it continued offshore, swimming near the seafloor but not reaching depths greater than 4 m until the following morning (*c*. 12 h post-release) before eventually reaching depths of 10 m and greater by the afternoon (*c*. 20 h post-release). There was a slight increase in activity (TBF) later in the day, while the heading and turning rates ($\bar{R}$ Index) of the estimated track fluctuated throughout as the shark gradually reached deeper water (Figure 2c,i II). Video footage confirmed the shark spent most of its time swimming close to the seafloor, with sand and seagrass patches seen throughout. Several potential prey species, including rabbitfish (*Siganus fuscenscens*), baldchin groper (*Choerodon rubescens*), pink snapper (*Chrysophrys auratus*), a whiptail stingray (possibly *Himantura fai*), and a Shark Bay sea snake (*Aipysurus pooleorum*) (Supporting Information Figure S1), were sighted. Some of these sightings were followed by periods of tortuosity, which can be indicative of foraging (Andrzejaczek *et al*., 2019), yet no attempts at prey capture were observed. Several small burst events were detected, and the tracking ended in a large burst event at 16.59 hours, the day after release. This event might be related to an attempted prey capture or a reaction to a potential threat, but there was no footage available from this time to confirm its cause.

A comparison with the data obtained from the wild tiger shark revealed some similarities but also differences in movement patterns, with the major differences seen in turning rates ($\bar{R}$ Index) and vertical velocity (m s^{-1}). A full summary of the data obtained for the three deployments, including the estimated straight-line distance the animals travelled, track length, average swimming depth, $\bar{R}$ index at 5 min intervals and a deduced average speed based on track length and time in kilometre per hour, is available in the supplementary materials (Supporting Information Table S1). For example, although the wild shark also made its way to deeper water (10 m+) around 12 h after tagging, it did so following a more direct path, displaying lower turning rates than the captive shark (Figure 2d). Vertical oscillations between the bottom and surface were seen throughout this shark's track (Figure 2i III), which is typical behaviour for tiger sharks in this region of Australia (Andrzejaczek *et al*., 2019). Horizontal movements only became tortuous once the shark had reached deeper water. Comparisons of the deployments reveal similar average activity levels between sharks, with slightly lower activity (TBF) recorded for the wild shark, which was expected because the wild shark was larger (Sato *et al*., 2007).

This case study is the first where high-resolution tracking using multiple movement sensors has been used to document the release of a captive tiger shark to the wild. The variable turning rates, non-

FIGURE 2 (a) The location of Ocean Park Aquarium within Shark Bay on the Western Australian coastline and estimated tracks obtained for the tiger shark released from the aquarium (Captive Post-Release, red) and of a wild tiger shark caught and released at nearby Big Lagoon (Wild Shark, orange). (b–d) Comparisons of the time series data obtained with the CamTag for the captive shark while inside the aquarium and post-release, and for the wild shark. These data include estimates of depth (charcoal), calculations of tail beat frequency (TBF; teal) and $\bar{R}$ index at 1 min intervals (blue). The latter were not available for the captive shark while in the aquarium due to the use of a magnet to disable the attached VHF transmitter. Thick black and teal lines represent the hourly rates of depth use and TBF, respectively. The thick blue line represents calculations of $\bar{R}$ Index at 20 min intervals. Also included are insets of *c*. 15-min intervals of movements from the captive post-release tiger shark's movements 3 h and 30 min (i I) and 22 h (i II) after release, and the wild shark demonstrating typical vertical oscillations 15 h after release (i III). Full time series including all metrics and data summaries are available in Supplementary Materials directional path and the extended period where shallow water movements were observed for the captive shark post-release may be explained by disorientation after a long period in captivity (Van Dykhuizen *et al*., 1998). Periods of disorientation are expected once animals are introduced or reintroduced to a new environment and are regularly observed in terrestrial programmes (Fritts *et al*., 1984; Moehrenschlager & Macdonald, 2003). The captive shark lacked recent experience of the wild and likely needed time to explore its new environment. The non-linear swimming of the captive shark may also reflect that it had not been able to swim in straight lines for prolonged periods since it began its time in captivity within a shallow, circular pool, and may similarly explain the lack of vertical oscillations in this shark compared to the wild-caught shark. In contrast, the wild shark swam almost directly to deeper water, where it remained for the rest of the deployment. Capturing sharks can heat internal temperatures, raise tail beats and initiate a flight response (Harding *et al*., 2022; Iosilevskii *et al*., 2022), and swimming to and remaining in deeper, potentially colder water may aid their recovery (Harding *et al*., 2022). The wild shark's more direct response likely reflects its familiarity with the environment, where it may have inhabited for a long period (Iorio-Merlo *et al*., 2022).

The wild caught shark was larger and caught earlier in the year than the captive shark; nonetheless, tiger sharks are found in Shark Bay year-round, and neither season or ontogeny was found to differentiate the fine-scale vertical or horizontal swimming of tiger sharks between these sizes elsewhere in Western Australia (Andrzejaczek *et al*., 2019; Meyer *et al*., 2014; Nowicki *et al*., 2019). The observable differences in the sharks' behaviours were most likely caused by the time in captivity and highlight the challenges faced by the captive tiger shark after release to the wild. A better understanding of these challenges is still needed to provide better guidelines for shark release procedures. Yet captive sharks elsewhere have survived the release process, with some displaying similar migration patterns and habitat use to wild tagged sharks within weeks of release (Marin-Osorno *et al*., 2017; Smale *et al*., 2012; Weng *et al*., 2012) and others have survived for years at liberty (Lee *et al*., 2015; Van Dykhuizen *et al*., 1998).

The results obtained with the CamTag provide unique insight into the release of a captive shark and the comparison of this shark's behaviour to one that has been living in the wild. Future post-captive studies should aim for longer deployment durations, which may reveal how long it takes to reduce the differences between the movements of the captive and wild sharks. However, increased deployment duration comes with an increased risk of tag loss. The continued collaboration between local aquariums and research groups, as well as the increased availability of high-resolution biologgers, means that larger data sets may become available in future. Such data sets would allow greater insights into captive-released sharks' survival rates and behaviours and the variability between species and individuals, providing best-practice procedures for ethical release of captive sharks that enhance post-release survival rates. Such procedures will strengthen public trust and contribute to greater sustainability in the aquarium sector.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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