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# DETAILED EXPERIMENTAL METHODS FOR "A MULTIVARIATE MIXED HIDDEN MARKOV MODEL FOR BLUE WHALE BEHAVIOUR AND RESPONSES TO SOUND EPOSURE"


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**1. Background: Research program and tags.** Our dataset includes observations of 37 blue whales collected offshore of southern California, U.S.A., as part of the Southern California Behavioral Response Study (SOCAL-BRS). SOCAL-BRS is an interdisciplinary research collaboration designed to study marine mammal behaviour and reactions to sound. Its overall objective is to provide a better scientific basis for estimating risk and minimizing effects of active sonar for the U.S. Navy and regulatory agencies. The overall experimental methods have been described in detail elsewhere (Southall et al., 2012). The current analysis is the first product of SOCAL-BRS to include MFAS transmissions from operational Navy vessels using full-scale sonar systems within CEEs (detailed below) in addition to simulations of such sonars using transducer arrays deployed from research vessels.

Before each CEE, whales were tagged with DTAGs (Johnson and Tyack, 2003). These animal-borne data loggers that record acoustic data in stereo at 64-240 kHz and 16-bit resolution, with most tags recording at 64 kHz. They also record high-resolution animal movement data, with on-board sensors including tri-axial accelerometers, tri-axial magnetometers, and a pressure sensor, all sampling at 50-200 Hz). Two whales were instead tagged with B-probes (Greeneridge Sciences, Inc., Santa Barbara, CA), which are similar to DTAGs. However, B-probes record acoustic data at a maximum sampling rate of 20 kHz, and their on-board sensors include a pressure sensor and 2-axis accelerometers sampling at 1Hz (and no magnetometer).

The tag data were calibrated, and whale-frame-of-reference depth, acceleration, magnetometer, pitch, roll, and heading data obtained, according to standard methods described in Johnson and Tyack (2003). Acoustic records from each tag were processed using custom scripts in Matlab software (The Mathworks, Natick, MA) to obtain flow noise in decibels root-mean-squared (dB RMS re 1 $\mu$Pa) in the 64–94 Hz band: after application of a 128-


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order 64-94 Hz bandpass finite impulse response (FIR) filter, the RMS noise level was computed in 1-minute windows sliding forward over the data by 0.2 seconds per measurement, resulting in flow noise measurements sampled at 5 Hz. Analysed tag recording durations were 1.3-5.6 hours per animal, including 6-93 dives per whale, and 0-16 dives during CEEs per whale. In total, the dataset includes 37 individual whales and 1054 dives, 168 of which overlapped with sound exposure periods.

In addition to the tag data, surface observations of animal positions and behaviour were collected by observers following the whales in a small boat. While the main research vessel (which operated the CEE sound source) had somewhat variable orientation with respect to the animal, a smaller boat typically remained within several hundred meters of the whale during the entire observation period. Observers on this small boat collected visual observations of the whales (such as precise locations of the whale's surface positions), and the consistent presence of this small boat helped to maintain a consistent context for behavioural observations (Southall et al., 2012).

**2. Controlled exposure experiment protocols.** Data were collected before, during, and after CEEs, in which whales were exposed to either MFAS or PRN sounds. The MFAS signals were either real (from a U.S. Navy vessel) or simulated (from a custom-built underwater transducer array). MFAS sounds included several tonal and frequency upsweep signals with frequencies between 3.2-3.6 kHz (real) or 3.5-4.05 kHz (simulated). The second signal type was PRN, which was band-limited noise in the 3.5-4.05 kHz band. Both signals had durations of approximately 1.5 seconds. Thus, PRN signal duration and frequency content was similar to MFAS, but lacking the tonal and FM upsweep component.

Each CEE consisted of multiple sequential signals presented at the nominal repetition rate of the common MFAS systems whose potential effects motivated the study. During all simulated MFAS and PRN CEEs, individual experimental stimuli (about 1.5 seconds in duration) were transmitted approximately once every 25 seconds, with an initial source level of 160 dB re 1 $\mu$Pa RMS at 1 m. The source level was increased by 6 dB per transmission until the maximum source level (210 dB re 1 $\mu$Pa RMS at 1 m for MFA or 206 for PRN) was reached; transmissions then continued at maximum level until the conclusion of the CEE. For the single real MFAS exposure, such a ramp-up was not feasible and is not part of normal naval operations. All transmissions were at the nominal source level for the SQS-53C sonar operated on the Navy ship participating in the study: 235 dB re 1 $\mu$Pa RMS at 1m. A repetition rate of one signal every 25s was used.

Simulated MFAS and PRN CEEs each lasted approximately 30 minutes in total, but the single real MFAS experiment was 58 minutes. The distance from the real ship to the subject whale in this case was prescribed as an approach from about 22-12 km, whereas the experimental source transmitting simulated MFAS and PRN signals was both much closer (nominally 1-2 km) and was stationary during CEEs. During the real MFAS CEE, the distance between the sonar transmitter and the whale was much greater in order to match the expected received level of the smaller sources. Because the source level of the

Navy ship's sonar was a constant 235 dB re 1 $\mu$Pa RMS at 1m, increased received signal levels at the whale position during the CEE were achieved by the ship's approaching the whale. Given this difference in protocols, the longer exposure duration was required to cover a comparable experimental range of received sound levels.

After CEEs, tag data recording continued until the tag detached from the animal (usually at least one hour, except in case of unplanned early detachment), and surface observations were also maintained for at least an hour post-CEE (except when prevented by darkness or when the animal was lost).

**3. Whale behaviour data.** Using the high-resolution, multivariate tag data and the the visual observations of behaviour and spatial locations, a number of variables were chosen to summarise the whales' behaviour. These variables were computed on a dive-by-dive basis; in other words, the input data for modelling were time series for which the sampling unit was one dive. Here, a "dive" was defined as any excursion from the surface to 10 m depth or greater. Dive start- and end-times were detected in the dive profile by visual inspection. The variables calculated for each dive were dive duration, post-dive surface duration, maximum depth, step length and turning angle in the horizontal dimension, number of feeding lunges, and variability of heading. Dive duration was the time (in seconds) from the start of a dive until the first surfacing following the dive. The post-dive surface duration was defined as the time (in seconds) from the end of one dive until the start of the subsequent dive. Maximum dive depth was the maximum depth attained by the whale over the course of the dive. To compute step lengths and turning angles based on position observations collected by human observers, we first used linear interpolation on the visual observation data on whale positions, which were unevenly spaced in time. The resulting interpolated tracks had a position estimate at the mid-point time of each dive. We verified the suitability of this simple track interpolation method by visual comparison of the original and interpolated tracks for all whales (data not shown).

We computed step length and turning angle based on the interpolated tracks. Step length was the rhumb-line distance travelled (in metres) between the mid-point of a given dive and that of the subsequent dive. The turning angle was the heading angle change (in radians) comparing the previous animal heading (defined by the vector pointing from the previous position to the current position) and the current animal heading (defined by the vector pointing from the current position to the subsequent position). The number of feeding lunges during each dive was determined by visual inspection of the tag depth, accelerometer, and animal orientation data, along with low-frequency flow noise levels from the tag acoustic recording; lunges were characterised by the distinctive combination of a vertical excursion in the dive profile (generally during the bottom phase of the dive) together with characteristic body pitch and a sudden deceleration evident in the body acceleration and flow noise data (here, flow noise intensity from the tag acoustic record served as a proxy for swim speed) (Goldbogen et al., 2006). Finally, variability of heading (heading variance) was computed from the DTAG heading data, using the circular variance, as appropriate for angular data (Zar, 2010). For a vector of $N$ angles $\mathbf{a}$, the circular variance is $1-\bar{r}$, where $\bar{r}$ is the mean resultant length $\frac{1}{N}\sqrt{(\sum_{n=1}^{N} cos(a_n))^2 + (\sum_{n=1}^{N} sin(a_n))^2}$; this variance ranges from 0 (no variation) to 1 (random variation in angles between 0 and $2\pi$).

The resulting dataset, including observations of dive duration, post-dive surface duration, maximum depth, step length and turning angle in the horizontal dimension, number of feeding lunges, and variability of heading, was used as input to the HMMs described in the main body of the paper. The data themselves are also available as an online supplement to the paper.

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