Supplementary Information: Optimising the use of bio-loggers for movement ecology research

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Table S1: Optimising the use of different sensors in bio-logging according to their function, strengths and limitations. Several sensors can be deployed to collect information relevant to the 'Big Questions' in movement ecology and may be deployed in combination to optimise the information gained (* - indicates combined use with other sensors). The sensor is linked to the question of interest in the Integrated Bio-logging Framework.

Bio-logger	**Description**	**Strengths**	**Limitations**	**Relevant Big Question**	**Optimisation**
(Tri-axial) Accelerometer	Measures acceleration due to gravity (*g*) in three axes (x, y, z) at sub-second frequency to infer posture and activity level.	Patterns in body posture and dynamic movement; energy expenditure (DBA: VeDBA, ODBA); intake quantification; small enough to be attached to specific limbs (biomechanics); acceleration can be used to infer beyond just "movement" i.e. internal state, evolutionary adaptations.	Long term continuous recording limited by current draw, on-board data storage and computer power in analyses, recording bouts and sleep modes should be considered; when quantifying patterns of movement in passive behaviour (i.e. when there is little change in dynamic acceleration) or when an animal pulls-*g* (i.e. change in speed).	Behaviour identification; 2D or 3D movement reconstruction*; energy expenditure; biomechanics; internal state.	Use in combination with sensors that provide orientation; consider attachment to the limbs separately to the body.

Bio-logger	**Description**	**Strengths**	**Limitations**	**Relevant Big Question**	**Optimisation**
(External) Ambient Temperature Sensor	Records environmental temperature at (sub-)second-based frequency.	Gives environmental temperature, although sensor equilibration pattern/response may limit this.	Temperature may be influenced by tag housing and attachment, and the animal's temperature/movement.	Space use; energy expenditure.	*In situ* remote-sensing.
Electroencephalography (EEG) logger (e.g. Vyssotski et al., 2006)	Records brain activity.	Insight into state-driven movements; internal state e.g. sleep; cognition and behaviour research.	Requires invasive electrodes to be implanted.	Internal state.	Use in combination with other sensors (movement and behaviour) to provide context of brain activity. Carefully evaluate impact on the animal.
Flexible Speed Paddle	Flexible paddle that bends in relation to flow rate. Can be recorded with infrared reflectance or a hall sensor.	Derive a speed estimation based on resultant current flow due to movement in air or water i.e. relative speed (e.g. Shepard et al. 2008); can resolve fine-scale changes in speed.	Requires complex calibration; resolution of data limited by properties of the paddle; if using infrared light, need to be corrected for temperature, turbidity and salinity.	Biomechanics; movement reconstruction.	Calibrated speed can inform dead-reckoning.
(Tri-axial) Gyroscope/ Gyrometer	Sub-second frequency measure of yaw, pitch and roll.	Determining how exocentric reorientations are related to egocentric rotations.	Long deployments with continuous recording, as high current draw and fast drift of the sensor.	Biomechanics.	Use in combination with other sensors to highlight details in locomotion patterns.
Hall Sensors (e.g. Wilson et al., 2003; Wilson, Steinfurth, Ropert-Coudert, Kato, & Murita, 2002)	Senses local changes in magnetic field strength in high resolution and at high frequency.	Can be attached to specific limbs or positioned at points where there is opposing movements or expansion e.g. IMASEN detects bites, breathing and vocalisations.	Potential hindrance to animal, requires careful positioning; requires calibration; possible interference with magnetic sensory system of the animal.	Energetics: foraging and defecation rates, heart rate and respiration; biomechanics.	Increased sensitivity and use of weak magnets can detect micro movements i.e. limb contraction.

Bio-logger	Description	Strengths	Limitations	Relevant Big Question	Optimisation
Heart Rate loggers	Measures bursts of heart rate pulses.	Heart rate can be linked to energy expenditure.	Loggers often have to be surgically implanted, which has ethical implications; heart rate measures of energy expenditure can be affected by other factors, such as stress.	Energy expenditure; internal state.	May be a proxy for internal state in terms of stress if dissociated from movement.
(Tri-axial) Magnetometer	Measures magnetic field strength in three axes (x, y, z), at sub-second frequency.	Determination of 3D orientation for dead-reckoning; in particular azimuth when coupled with a tri-axial accelerometer (required to infer the horizontal plane in which azimuth is measured).	Output is influenced by magnetic material and hard and soft iron distortion.	Behaviour identification; 2D and 3D movement reconstruction*; biomechanics.	Use in combination with other sensors (accelerometer at high frequency to resolve orientation and GPS at lower frequency to correct drift in movement reconstruction); Possible interaction with magnets utilised in Hall sensors for limb movement.
Microphone sensors	Ambient sound.	Infer environment of the animal; record sound produced by other individuals (e.g. vocal cues); identify specific behaviours coupled with sound; feed learning machines; can infer relative speed in marine animals (through the sound of water flow).	Difficult to isolate the sound of interest in noisy environments; difficult to attribute direction of sound.	Social interactions. Predator prey interactions.	Couple with acceleration to identify movements involved in sound production (e.g. vocal cues picked up in the movement of a collar).

Bio-logger	**Description**	**Strengths**	**Limitations**	**Relevant Big Question**	**Optimisation**
Molecular recognition nanosensors (e.g. Landry et al., 2014; Lee et al., 2018)	Molecular recognition sensors, e.g. hormones, nutrients etc., based on the Corona Phase Molecular Recognition method.	Physiological bio-logging; provides insights into the internal state of the animal.	Requires invasive implantation.	Physiological/ internal state.	Use in combination with movement and behaviour sensors. Carefully evaluate the impact on the animal.
Passive Acoustic Telemetry (e.g. Johnson & Tyack, 2003)	Senses a tagged marine animal passing by a stationary acoustic receiver.	Allows long-period tracking of tagged animals; collects network data.	Detection range can be limited; can be affected by environmental variables such as the wind.	Behavioural patterns, feeding/ foraging/ resting segmentation, interaction of individuals and species.	Use of arrays to localise animals.
Pitot Tube	Differential pressure sensor (*volts*); differential between forward facing pressure sensor and covered barometric pressure sensor.	Derive a relative airspeed in relation to airflow (Williams et al. 2015). Can be adapted to work in both air and water mediums (see Takahashi et al. 2018).	Requires calibration or high-resolution environmental airflow data i.e. wind speed and direction; needs to protrude out of the device for clear flow i.e. no obstruction to oncoming airflow. Can be used only on animals that move fast with respect to the medium, and often requires that the medium velocity can be determined in some way for correction.	Movement reconstruction*; biomechanics.	High temporal and spatial resolution wind data improves accuracy.
Pressure sensor (e.g. Shipley, Kapoor, Dreelin, & Winkler, 2018)	Measures pressure (*Pa*) at sub-second frequency.	Proxy for depth and/or elevation.	Must be regularly corrected for sea level pressure for zero offset correction when used in air.	3D movement reconstruction*	High frequency records for local Sea Level Pressure improves accuracy (e.g. hourly to sub hour records).

Bio-logger	**Description**	**Strengths**	**Limitations**	**Relevant Big Question**	**Optimisation**
Proximity sensors	Animal borne transceivers; detect proximity based on radio signal strength.	Detect presence of nearby tagged animals; tag-to-tag communication between individuals.	Involved calibration and processing; high current draw, limited deployment duration, days to weeks.	Social interactions; space-use.	Use visualisations to map spatio-temporal environment from logged encounters.
(Animal-borne) Radar detectors (e.g. Weimerskirch, Filippi, Collet, Waugh, & Patrick, 2018)	Detect radio signals of specific radar bands e.g. radar emitted from a vessel; meteorological radars.	Interactions between marine animals and boats; link to foraging at vessels; identification of migration fronts; can measure distance between transmitter and receiver.	Currently can only be deployed on larger species capable of carrying larger devices.	Animal-human interaction; bio-logging for conservation; foraging.	Compare with vessel identification systems to locate illegal fishing vessels.
Speed Propellers (e.g. Ropert-Coudert et al., 2001)	Propeller or turbine rotated by ambient water flow.	Measure speed of marine animals if calibrated against the flow rate.	Excessive drag; low resolution; susceptible bio-fouling and damage.	Foraging behaviour; biomechanics.	Provides speed for dead-reckoning.
Stomach Temperature sensor (e.g. Hedd, Gales, & Renouf, 1995; Wilson, Cooper, & Plötz, 1992)	Ingested, records internal temperature.	Determine prey acquisition based on prey temperature.	Tag housings may act as insulation and need to be corrected; loggers need to be recovered from stomach contents.	Feeding activity; energy expenditure.	Use with externally attached device to transmit data remotely.
Video loggers (e.g. Moll, Millspaugh, Beringer, Sartwell, & He, 2007; Rutz, Bluff, Weir, & Kacelnik, 2007; Tremblay, Thibault, Mullers, & Pistorius, 2014)	Visually records animal and its environment.	Observe behaviour visually when direct means are not available; adds environmental context and the behaviour of others in view; can be used to ground truth measurements of other sensors to use in machine learning.	Deployment duration limited by battery capacity (though if longer recording times are required, a lower frame rate may be acceptable); constrained to species of certain size, movement mode and ecology; processing time-consuming and computationally demanding; high storage capacity required.	Behavioural identification; social interactions; foraging behaviour; space-use.	With advancements in the miniaturization of cameras can reveal cause and consequence of behaviour in terms of the world around the animal.

Table S2: Glossary of key movement ecology terms

Azimuth	Orientation of the surge axis in the XY plane with respect to some geographical direction (usually East or North).
Bank angle	(or lateral inclination) Orientation of the sway axis with respect to the horizontal level, measured orthogonally to the surge axis. It is undefined when the surge axis is vertical.
Egocentric frame of reference	Animal-bound defined by surge, sway and heave axes, or equivalently by coronal plane (orthogonal to heave axis), sagittal plane (orthogonal to sway axis, and frontal plane (orthogonal to surge axis).
Elevation angle	(or longitudinal inclination) Orientation of the surge axis in the vertical plane, at the current azimuth. It is restricted to the [-90°, 90°] range.
Exocentric frame of reference	Environment-bounded defined in 3D by two horizontal axes, x and y, and a vertical axis, z. In 2D, only two axes, x and y, are considered, and are not necessarily horizontal.
Heading	In 2D, azimuth; In 3D, azimuth and elevation angle.
Location	Point in space defined by a couple (2D) or triplet (3D) of Cartesian coordinates (x,y or x,y,z).
Movement	Path (i.e. the purely spatial component of movement) and associated temporal component (movement is usually recorded as a time series of locations).
Path	Ordered series of locations without timestamp.
Position	Location and heading.
Posture	Combination of elevation and bank angles (also referred to as attitude).
Reorientation	In the exocentric frame of reference, change in heading (called turn or turning angle in 2D). In the egocentric frame of reference, corresponds to yaw (2D) or a combination of yaw and pitch (3D)
Surge, sway and heave axes	Axes of animal’s body corresponding to the posterior-anterior, right-left and ventral-dorsal axes, respectively.
Track	Recorded movement or path (depending if the time has been recorded or not).
Trajectory	*Sensu stricto* corresponds to a purely advective (i.e. ballistic) movement, but it often used as a simple synonymous of movement or track.

Velocity	Speed and heading.
Yaw, pitch and roll	Rotations in the coronal plane (around the heave axis), sagittal plane (around the sway axis) and frontal plane (around the surge axis), respectively.

Box S1: Step selection with behavioural state

This technique parameterises a movement kernel that describes the probability, $p(x_{t+\tau}|x_t, Z, \beta)$, of an animal being at location $x_{t+\tau}$ (or in other cases, position, incorporating aspects of posture and heading for example) at time $t+\tau$, given that it was at location x_t at time t, where Z is a vector of environmental features hypothesised to covary with the movement from x_t to $x_{t+\tau}$, and β is a vector denoting the strength of each hypothesised covariate (see e.g. Avgar et al. 2016). For example, Z may contain an entry detailing the expected resource quality between x_t and $x_{t+\tau}$, or whether there are barriers to movement between x_t and $x_{t+\tau}$, and so forth (see Thurfjell et al. 2014). In extending our model to examine changes in state, for example, we might parametrise a model $p(X_{t+\tau}|X_t, Z, \beta)$, where X_t and $X_{t+\tau}$ are vectors containing movement features such as internal state, energy expenditure or environmental variables.

Table S3: Recent visualisation studies for movement ecology

Data type	Visualisation approach	Reference	URL of the tool/code
Movement path & trajectories	Space use over 2D geographic space and time	Demšar, Buchin, van Loon, & Shamoun-Baranes, 2015	https://github.com/udemsar/SpaceTimeDensities
	Space use with environmental information	Buchin et al., 2015	Code provided as supplementary information of the paper
		Remelgado, Wegmann, & Safi,	https://cran.r-project.org/web/packages/r

Data type	Visualisation approach	Reference	URL of the tool/code
		2019	sMove/index.html
	Space use over 3D geographic space	Tracey et al., 2014	Pseudocode in paper
		Demšar & Long, 2016	To be available soon at http://github.com/udemsar
		Ferrarini, Giglio, Pellegrino, Frassanito, & Gustin, 2018	/
	Temporal visualisations for bird migration	Kölzsch, Slingsby, Wood, Nolet, & Dykes, 2013	/
		Slingsby & Van Loon 2016, 2017a,b	http://gicentre.org/birdGPS
	Animation	Schwalb-Willmann 2018	https://cran.r-project.org/web/packages/moveVis/index.html
		Scharf 2018	https://cran.r-project.org/web/packages/anipaths/index.html
	Visual analytics tools – linked views with many spatio-temporal & environmental visualisations	Dodge, Xavier, & Wong, 2018	https://conservancy.umn.edu/handle/11299/197620
		Konzack et al., 2017, 2018	http://www.win.tue.nl/~kbuchin/proj/gullmigration/
Behavioural sensor data	3D visualisation of tri-axial accelerometry and magnetometry data	Williams et al., 2017; Wilson et al., 2016	http://wildbytetechnologies.com/software.html
Bird migration data from	Vector field visualisations for bird migration flows	Shamoun-Baranes et al., 2016	https://github.com/enram/bird-migration-flow-

Data type	Visualisation approach	Reference	URL of the tool/code
meteorological radar			visualization
Flow data	Flows between static RFID stations	LaZerte et al., 2017	https://github.com/animalnexus/feedr
	Space use from acoustic array data – activity seascapes	Papastamatiou et al., 2018	https://github.com/udemsar/ActivitySeascapes

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