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Review

Subjectivity in bio-logging science: do logged data mislead?

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Abstract: Logging of data using animal-attached archival units (bio-logging) involves potential sources of subjectivity that are reviewed in the present paper. Subjectivity may be the result of technical limitations of which the selection of the correct sampling frequency is particularly critical. Mistakes or aberrant data can also result from transitory defaults in the loggers functioning. Similarly, the use of purpose-written software to pre-process logged data before analysis is another step during which substantial modification of the raw data can occur. Apart from technical limitations, bio-logging devices are also known to modify the behaviour of the animal studied. Finally, arbitrary conclusions can eventually be drawn out from the 'visual' analysis of logged-data. The second part of this review proposes a non-exhaustive list of precautions so as to enhance objectivity in bio-logging approach. Among these precautions, assessment of the impact that data-logger may have on the animal, appropriate calibrations (for example for transformation of the raw measurements into useable variables) and multi-data sampling are useful steps in bio-logging utilization.

key words: data logger, resolution, sampling interval, calibration, impact of devices

Introduction

Classical areas of biological science have always suffered from the restrictions inherent in their definition. For instance, if physiology represents a rigorous methodology and provides quantified information, it generally concerns only organs or whole animals isolated from their environment. Similarly, while behavioural science studies whole animals, it primarily deals with captive individuals for which continuous and measurable observations are possible. In contrast, population ecology often aims to link the individual's variables to its environment and to other members of its biotope. This challenging task often lacks rigorous laboratory controlled conditions so that probabilistic models become a primary tool. In other words, although controlled laboratory studies allow a measure of objectivity, they are often disconnected from the reality of organisms living in their proper environment. Conversely, ecological studies deliver global information with a high risk of subjectivity.

Logging of data using animal-attached archival units—also termed "bio-logging"—has recently emerged as a new area of science that could combine the rigor of controlled conditions with the acquisition of detailed data measured *in situ*. Indeed, such methods offer a way of quantifying the behaviour of free-ranging individuals. The ecophysiology and behaviour of marine top-predators have been extensively investigated over the past three decades, central place foragers being of particular interest in these types of studies due to the facility with which deployed units can be recovered. Bio-logging makes use of data loggers that record variables while directly attached to, and even sometimes implanted in, the study animals. These variables are generally recorded in the memory of the devices over time. Data are sampled at various frequencies, depending on the capacity of the logger and the purpose of the study. Upon recovery of the logger, following a period during which the animal has performed various activities, data are downloaded into a computer, formatted and analyzed. Although the principle of such studies implies that the data are obtained directly from normally-behaving individuals exploiting their environment and responding to other animals, the successive steps required to obtain these data, from the sampling program to final analyses of the data, has a subject element. By "subjective" we refer not only to biases that result from pre-conceived notions of how these animals behave but also to biases resulting from technical failures or from the way the data are recorded. In order to define and set the limits of bio-logging as an independent area of science, it is appropriate to review and discuss the level of subjectivity that bio-logging science engenders. The present review aims at summarizing potential sources of subjectivity inherent in bio-logging studies and to present a list of a few precautions that may enhance objectivity.

Sources of subjectivity

Technical limitations

Temporal resolution:

Selection of the correct temporal resolution, defined by the sampling interval, is critical for effective logging (Wilson *et al.*, 1995; Boyd, 1993) and depends on whether the experiment involves the simple recognition of events or whether the extent of individual events is to be defined. For recognition of events, the sampling interval must be at least less than the length of the event to be recognized. One way to do this that minimizes the recording frequency, and thus extend the recording life of the unit before the memory is full, is to use a sampling interval that corresponds to the length of time between the two minimum thresholds for detection on either side of the peak height of the event. An example of this is the detection of prey swallowing (Fig. 1a). Otherwise, a standard value would be that the interval should be *ca*. half the length of the event, for example the detection of prey swallowing (Fig. 1b). However, selection of an appropriate sampling frequency in the case of cyclic phenomenon for which the period varies drastically over time can be difficult. For instance, the heart rate of free-living diving animals such as emperor penguins *Aptenodytes forsterii* can vary from 30–213 beats/min (Kooyman and Ponganis, 1994). In this particular case, the best remedy is to obtain simultaneously an analog record of the heart rate to verify the digital record for a period (G.L. Kooyman, pers. communication). If the form of the event is to be described *via* changing values then the recording frequency should be such that of the order of ten measurements should be made per event (Fig. 1c). Even so, it should be borne in mind that where peak values in the measured event are important, such as in measurement of wing beat amplitudes, recording frequencies of event length/10 may not adequately describe peaks (Fig. 2).

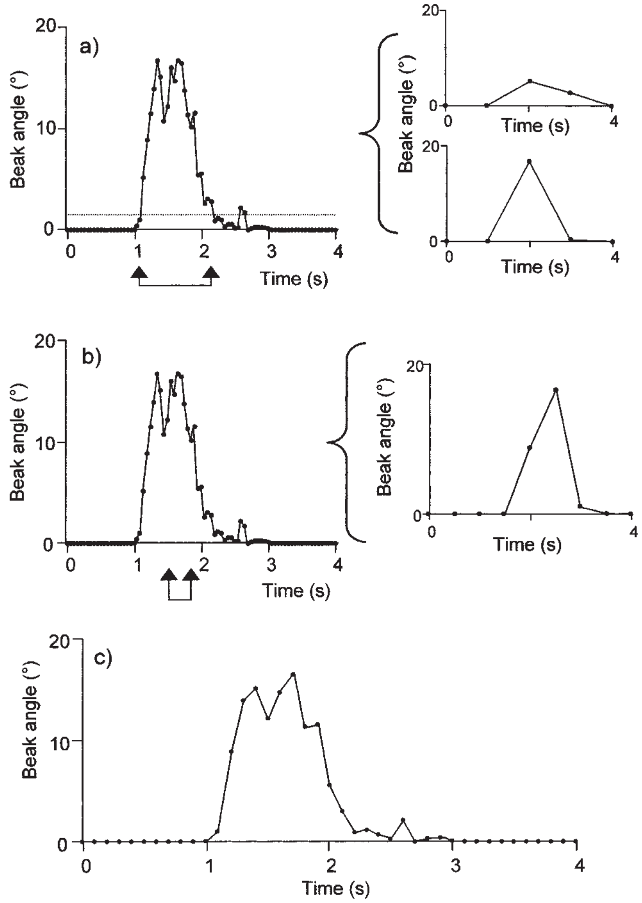

Fig. 1. Examples of how the sampling rate used in loggers influences the quality of the data obtained. (a) shows the ingestion of a prey item by a Magellanic penguin *Spheniscus magellanicus* as defined by an IMASEN (see Wilson *et al.*, 2002) recording at 20 Hz. This same information is presented recorded at 1 Hz (two figures to the right), this frequency being derived from the minimum length of time necessary to record at least one measure over a specified threshold (here 2°—see arrows) per event. The two figures on the right show two scenarios which arise from the logger recording at two slightly different times. (b) shows recording of the ingestion of prey by a Magellanic penguin at 2 Hz (right hand figure), this frequency being defined as the length of time comprising half of the length of the actual event (see arrows in left hand figure). (c) shows the definition obtained by defining the ingestion event shown in (a) by approximately 10 points (recording frequency 10 Hz).

Bit resolution:

The quality of the data obtained depends critically on the number of bits with which the data are stored. Many devices still use 8 bit resolution, which only allows an absolute resolution (assuming that the sensor is perfect) of the maximum measuring range divided by 256. For example, a perfect pressure transducer measuring over a range of 50 Bar will only have a maximum step resolution of *ca.* 0.2 Bar or about 2 m depth. Ten, 12 and 16 bit resolution, however, will allow steps of 0.49 m, 0.12 m and 0.008 m. Assuming the transducer to be perfect, higher resolution therefore leads to massively better depth definition so that, for exam-

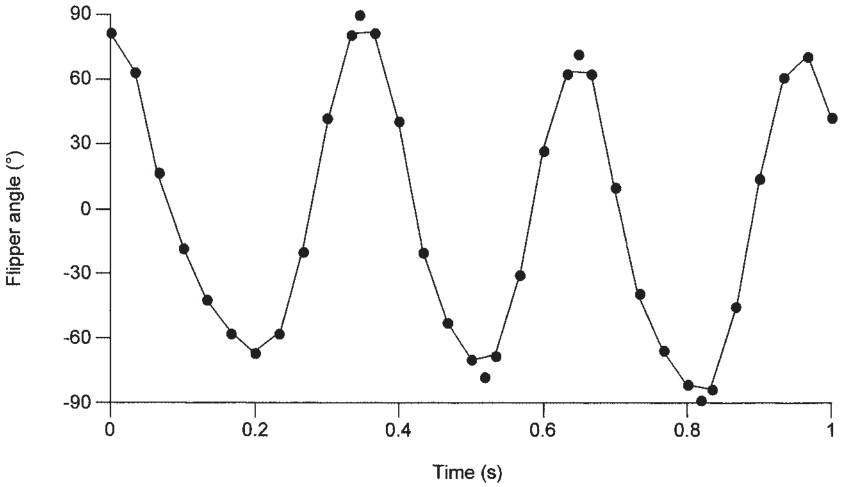

Fig. 2. Flipper position in a diving Magellanic penguin *Spheniscus magellanicus* over 1 s in which three flipper beats are recorded. Flipper angle corresponds to +90° = maximum downbeat and –90° = maximum upbeat. Although recording frequency was 30 Hz so that approximately 10 points define one cycle (see Fig. 1c), the positions of maximum amplitudes (shown by unconnected dots) are not recorded.

ple, body movements in the vertical axis due to locomotory movements can be examined if the temporal resolution allows it (see above).

Accuracy of the sensors:

The best logger resolution does not lead to storage of high resolution data unless the transducers give appropriate, good quality signals. In a general sense, smaller sensors tend to be less accurate (this is particularly true for pressure and light sensors), something that tends to run counter to bio-logging requirements because devices need to be constructed as small as possible. In addition, the output of almost all solid state-based transducers is temperature dependent so that some appropriate form of temperature correction must be undertaken (*e.g.* Liebsch, 2002). This is nominally done by locating a temperature sensor close to the transducer to be corrected. However, differing response times between the transducer and the temperature sensor can still lead to problems, particularly when boundaries of substantial changes in temperature occur such as at the water/air interface.

Independent of this, the ultimate accuracy and utility of many transducers used in heterogeneous environments depends on their response time. This is often a function of size (*e.g.* in temperature sensors - and this includes the sensor plus associated packaging) and in angle (orientation) sensors depends on whether the transducers are liquid-filled. In the latter case, animal movement may produce slopping in the liquid which needs up to a second to stabilize.

Instantaneous measurement of speed is particularly problematic. Speed sensors should be calibrated on life-size models of the animals so as to emulate water flow conditions over the body. However, even this may be inaccurate since the stroking behaviour of animals associated with movement may produce turbulence that affects the response of the transducer (unpublished data).

Putative behaviour and real-false events:

Mistakes or aberrant data can also result from transitory defaults in the loggers functioning.

In some instances, these defaults arise from technical failures, such as in the case of temporary reversal of the sensor's polarity, but they can also be the direct consequence of the physical parameters of the environment. Propeller-based swim speed recorders mounted on marine mammals or seabirds may deliver slow speed or no values when algae, sand or ice

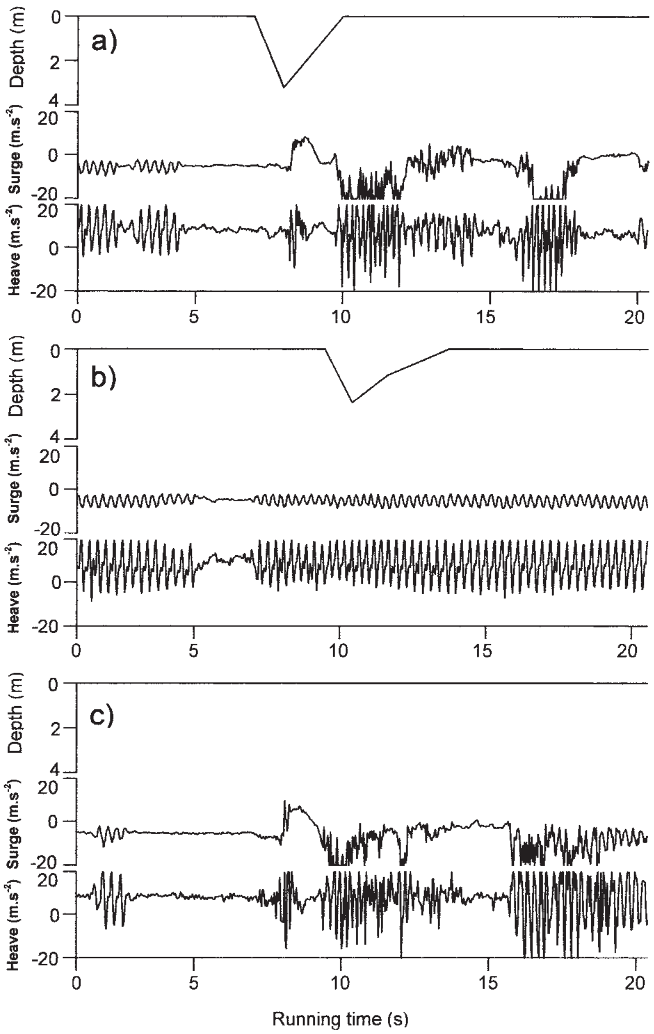

Fig. 3. Signals recorded by a depth and two-way acceleration miniaturized data-logger attached to the central tail feathers of a breeding Cape gannet *Morus capensis*, foraging off the coast of South Africa in 2002 (Y. R-C. unpublished material). Each graph displays the diving depth (top lines), the acceleration recorded on the surging axis (*i.e.* front-rear acceleration; middle line) and the acceleration recorded on the heaving axis (*i.e.* dorso-ventral acceleration, bottom lines). Flapping flight is detected as a synchronous oscillating pattern on the heaving and surging axes. A plunge event (*i.e.* aerial plunge and the subsequent underwater phase) when correctly detected on each channel (a), corresponds to a classic depth profile associated with complex signals on the acceleration axes, among which an abrupt deceleration and an invertion in the general direction of the heave acceleration are always present. The graphs in b) and c) show examples of a false dive appearing during a flapping flight sequence and a clear plunge trace as recorded on the acceleration axes with no depth profiles, respectively.

accumulate on the propeller. Total failure is sometimes more advantageous than intermittent faults because no data are collected, which eliminates the possibility of misleading interpretations (Kooyman and Ponganis, 2004). On the other hand, interference that affects the calibration is much worse because it may go undetected. Consider, for example, a paddlewheel turning more slowly because of algae contamination. The final analysis might be reporting a slower swim speed and less distance traveled than actually happened. This kind of a problem might be difficult to detect during the testing stage of the logger.

Prior to the analysis, data stored in the logger memory often need to be pre-processed in order to adjust raw measurements by the transducers to correct values. Such adjustments are necessary. For instance, pressure transducers are temperature sensitive and zero for the surface of the water may change in relation to the characteristics of the transducer and the ambient temperature. The correction can be performed using software that is provided by the manufacturer or by the user. However, zero-align methods, which are based on the principle that depth values are equal to zero when the bird is at the surface, may modify the maximum depth of dives if they are conducted automatically and over a large scale. In the case of shallow divers, because the offset values are sometimes greater than the dive, these methods can also erase genuine dives or create false dives. False or absent dives can be easily detected when additional information on the activity of animals, through accelerometers for instances, can be gathered simultaneously with depth data such as in the case of plunging Cape gannets *Morus capensis* (Fig. 3). Here, two-way accelerometers allow us to identify flapping and gliding flights, plunge events, time spent at the sea surface and take-off activities (Fig. 3a). This information can be compared to the signal recorded by the pressure transducer so that false dives (Fig. 3b) and absent dives (Fig. 3c) can be identified.

Biological model limitations

Modification of animal behaviour due to units:

It is now commonly acknowledged that devices attached to animals may have adverse effects on their behaviour (*e.g.* Ropert-Coudert *et al.*, 2000a), as well as individual fitness, and directly or indirectly affect performance (Wilson *et al.*, 1986; Culik *et al.*, 1994). Consequently, breeding success may be jeopardized (see Kooyman, 1989; Wilson and Culik, 1992 for reviews of logger effect; Hull, 1997). The impact of loggers differs according to the species considered and the logger characteristics. To consider only a few examples: 1) the hydro- and/or aerodynamic modifications to streamlining induced by units attached on the body of animals (Bannasch *et al.*, 1994), 2) the extra-weight added to the body mass of flying birds (Croll *et al.*, 1992), 3) the increase in the agonistic behaviour of conspecifics (Wilson and Wilson, 1989), or 4) compromised natural camouflage of animals (Wilson *et al.*, 1990). It is important to note that some detrimental effects, such as reduced brood provisioning rate, are not always as easily detected as impairment in the bio-mechanical well-being of the study animal. Even a seriously encumbered animal may still undertake apparently normal activity due to breeding requirements, hunger, or the drive to migrate. Our subjective assessment that an animal is performing "normally" is probably one of the weakest links in the chain of events from logger design, testing, implementation, to analysis and interpretation of results.

Visual analysis, the subjective eye:

Conclusions from observation of data can also be false. For instance, classic time-depth

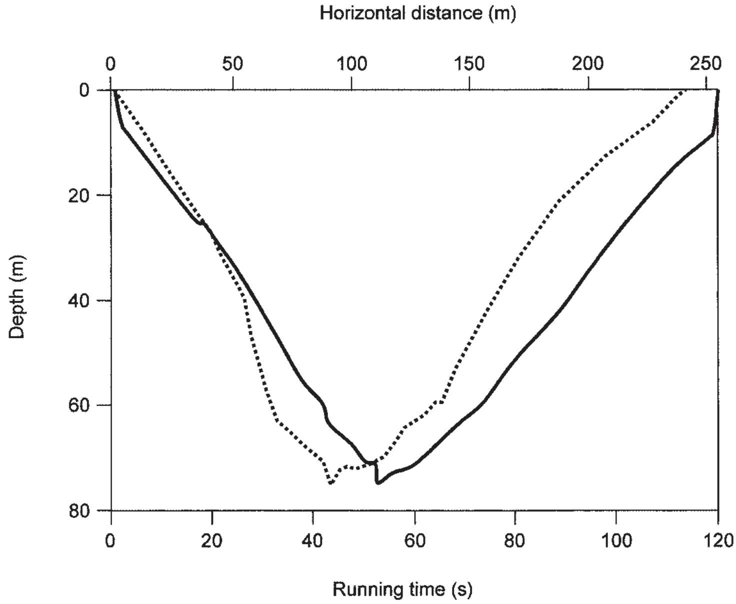

Fig. 4. Profile of the dive of an Adélie penguin, *Pygoscelis adeliae*, resulting from a time-based approach (depth data are expressed as a function of time, dotted line) and a distance-based approach (depth data are expressed as a function of time but corrected by the angle of diving as deduced from the simultaneous measurement of the swimming speed of the bird, solid line).

recorders on animals diving a 3-D path compress it into two dimensions only, *i.e.* time and depth (Fedak *et al.*, 2001). Thus, arbitrary conclusions can eventually be drawn out from the 'visual' analysis of the shape of dives (*cf.* Wilson, 1995), especially when compared between species. On a time-based depth data series, information on dive angles is lost and the underwater path may look very different depending whether it is time-based or distance-based (Fig. 4). Simultaneous measurements of the swimming speed (Ropert-Coudert *et al.*, 2001), acceleration data and/or the 3-D movements of the animals using geo-magnetic gimbaled compasses, a.k.a. the 'dead reckoning' method (*e.g.* Wilson and Wilson, 1988; Wilson *et al.*, 1991; Mitani *et al.*, 2003) can help correct this problem (see the section 'remedies', 'Multi-data sampling' chapter below) since these additional data provide us with a measure of the diving angle and thus the horizontal diving path. However, an increase in the number of variables monitored simultaneously generally results in an increase of the size of the logger, restricting their use to larger animals. In this regard, the use of a dimensionless, depth and duration independent index (TAD for Time Allocation at Depth, Fedak *et al.*, 2001) may prove useful in interpreting diving activity *a posteriori* and facilitating inter-specific comparisons.

Remedies

Estimation of logger impact

Assessing the level of impact that data-logger may have on the animal is a useful, if not essential step, in bio-logging experiments. There are two aspects to consider when dealing with bio-logging investigations: the duration of device deployment and the status of the species investigated. If the experiment is short-term (arbitrarily, this may correspond to a period within the bounds of a foraging cycle) the level of interference with normal activity is less crucial, than if the deployment is long term. For example, placing a large backpack on an athlete doing a 100 m dash to determine peak heart and respiration rate and blood pO_2 would ruin his/her performance time, but not necessarily the results manifested in the cardiovascular response to intense exercise. On the other hand, the same package applied to a marathon runner could cause the athlete to be unable to finish the run. Similarly, a device-induced encumbrance to measure a single foraging trip may provide the basic pattern of foraging, but the criteria for a device to determine the foraging behavior throughout the year would be quite different. For instance, the crittercam video-camera, although being a source of exciting, new information on the underwater activity of diving animals, cannot be deployed on small, free-ranging individuals and its use is, therefore, highly dependent on the access to specific experimental sites such as the "isolated dive hole" (see Ponganis *et al.*, 2000). For long-term investigations, the cumulative effect of externally-attached packages can be avoided by implanting the devices under the skin (*e.g.* Butler and Woakes, 2001). Implantation, however, implies surgical procedures that should be performed by competent researcher, with the ability to perform anesthesia and surgery (see Hawkins, 2004 and references therein for guidelines on surgical procedures). In the case of implanted devices, the recovery rate of animals after release becomes a major issue for the device may remain *ad vitam eternam* inside the animal, contrary to externally-attached loggers.

Similarly, issues will be different according to the status of the animal studied. Access to endangered species is generally restricted and bio-logging investigations in such cases suffer from a drastic reduction in the sample size of the individuals that can be equipped. Added to a poor recovery rate, this may dampen the amount of exploitable data that can be obtained.

Guidelines for reducing the effect of loggers on animals, such as using a non-conspicuous colour, a point of attachment on the animal that minimizes the drag, and a method of attachment that preserves the integrity of the plumage or fur and shorten the necessary handling time during instrumentation (*e.g.* TESA tape, Wilson *et al.*, 1997) already exist (Wilson and Culik, 1992; Hawkins, 2004 and references therein). In a practical way, it is important to ensure that animals equipped with loggers i) can exhibit the same range of performances that non-instrumented animals do over the whole or a part of their biological cycle, and that ii) their physical and physiological fitness does not deteriorate due to logger attachment, and iii) their breeding cycle has not been modified. These precautions involve a considerable effort in the field work with the tracking of the animal's behaviour after the period of instrumentation. It also implies that researchers should constantly try to minimize the stress resulting from an animal's manipulation (Le Maho *et al.*, 1992).

Calibration

The calibration phase in a bio-logging approach is important for a number of reasons. These experiments may be used to:

i) *estimate the degree of tolerance of the animal to the loggers:* (assuming that captive individual of the same species or at least a closely-related one, are available for experimentation). Signs of nervosity (*e.g.* an increase in preening activity) caused by the loggers or some parts of it such as cables, magnets, aberrant behaviour (*e.g.* aggression), physical or physiological impairment (*e.g.* loss of appetite, cuts, scars...) are expected symptoms from a disturbed subject.

ii) *transform raw measurements into useable variables:* For example, propeller-based swim speed data-loggers record the number of rotation of the propeller per second and this must be transformed into genuine swim speed. This can be done in several ways: by using controlled conditions, such as in a water tank where the propeller response can be related to known flow velocity, by pulling the speed logger in the water at known speeds or by post-deployment methods, where depth data are used to derive the speed values (Fletcher *et al*., 1993; Blackwell *et al*., 1999).

iii) *define the best placement for data-loggers on the animal's body:* Similarly, experiments on captive specimens may prove useful for testing the extent to which logger attachment position is important: The water flow over an animal's body is not the same at each point and researchers have to select the location for the logger that will not only create the smallest drag but also record the most accurate speed values (Bannasch, 1995). Note that these two concepts are often incompatible and calibration experiments are thus, required to correct the values recorded on free-ranging individuals. An example of this is the change in the posture and behaviour of Little Penguins *Eudyptula minor* equipped with unbalanced devices (Healy *et al*., 2004).

iv) *relate signals recorded by loggers to behaviour of animals:* If some calibration can be performed on carcasses or models of animals, the use of live subjects, moving freely in an environment similar to their natural one, is of importance if one wishes to relate the output of the sensor to an actual behaviour that occurs in the wild. Although in most cases, this calibration phase is a valuable source of information, the behaviour of captive individuals may differ to some extent from that of free-ranging animals (*e.g.* prey pursuit in a pool with no escape possible for the prey). Researchers dealing with free-ranging animals may end up investigating putative behaviour despite having performed robust calibration tests on captive subjects.

Multi-data sampling

Calibration experiments cannot always be performed due to the extreme nature of the activity that researchers are investigating. Thus, as noted earlier, relating the sensor output to an observed activity may prove particularly challenging, such as in the case of Cape gannets plunging from high into the water (Nelson, 1978) or emperor penguins diving to depths over 500 m (Kooyman and Kooyman, 1995). In order to reduce the source of errors in the interpretation of the logged data, multi-data sampling may prove useful. The acceleration signals of Fig. 3 are, for instance, a useful way of detecting false dives from genuine ones. In some instances, environmental variables obtained simultaneously with logged data (through remote sensing systems) is useful for calibrating and interpreting the data recorded by devices. Block *et al*. (1998) obtained confirmation on the exact location of an Atlantic bluefin tuna, *Thunnus thynnus thynnus*, in the North Atlantic waters by comparing temperature data recorded by an archival tag attached to the fish and Sea-Surface-Temperature data acquired from Advanced Very-High Resolution Radiometer.

Conclusions

The success of bio-logging is highly dependent on technological progress and features such as miniaturization, improvement in sensor resolution, increase in the available memory size, etc. These technological advances have allowed workers largely to overcome some of the sources of subjectivity evoked in this paper. Note that the costs of such technology or the difficulty in deploying it on animals that are considered to be 'sensitive' to human perturbation, may sometimes limit the boundaries of an experimental study. This results in a small sample size of instrumented animals, which may be regarded critically by statisticians with regard to acquiring meaningful results.

Although bio-logging is still mainly confined to studies dealing with large marine animals, it has recently undergone a phase of expansion where smaller individuals as well as terrestrial and aerial species have been involved. Such expansions and the inter-disciplinarity of bio-logging studies will open up many of the secrets of wildlife *hitherto* unattainable, but also bring with it its own elements of subjectivity that will have to be dealt with as they come.

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