Sensors for ecology

Towards integrated knowledge of ecosystems

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"A diver inspects a queen conch *Strombus gigas* during a scientific expedition in Mexico. The queen conch is equipped with acoustic sensors, here nearby a receptor, in order to collect information on its behaviour and physiology in nature."

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I

ECOPHYSIOLOGY AND ANIMAL BEHAVIOUR

Chapter 1

Bio-logging: recording the ecophysiology and behaviour of animals moving freely in their environment

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1. Setting the scene

1.1 Sensing with bio-loggers

Bio-logging refers to the fastening of autonomous devices onto (mainly) free-ranging animals to collect physical and biological information (Naito, 2004; 2010; Cooke et al., 2004; Ropert-Coudert et al., 2005; see also Costa, 1988, although the term bio-logging was not used in these times). It should be noted here that bio-logging is sometimes referred to as biologging. However, as Naito (2010) pointed out, the latter term is misleading as it is used in molecular biology. As such bio-logging differs from telemetry in the sense that data are stored locally in the memory of the devices and not transferred *via* radio waves or other transmitting means. This move from biotelemetry to bio-logging was done in order to address practical difficulties related to data transmission. Thus, this comes, as no surprise that bio-logging was firstly used in ecological and physiological studies to investigate marine, far-ranging, diving species, as water represents a barrier to radio signals. Bio-logging studies were initially conducted on species with a body mass large enough to accommodate the large size of the very first loggers: seals and whales. As miniaturisation progressed, smaller species of seals and seabirds became target species for bio-logging approaches. Among seabirds, penguins (*Sphenscidae*) represent an intensively studied family because of their adaptation to aquatic life and their consequently denser, larger and more robust body. Nowadays, bio-logging can be applied onto an impressive range of species, terrestrial or aquatic, whether these are mammals, birds or reptiles (see I, 2). Bio-logging developments are one step away from moving into the insect realm as radio-telemetry is already available to study terrestrial and flying insects (Vinatier et al., 2010; Wikelski et al., 2006).

Immediate consequences of local storage are the necessity to retrieve the device to access the data and develop appropriate sensors to gather data about physical and biological information on relevant time scales. It therefore clearly appears that bio-logging primarily refers to a methodological approach and has generated research to improve existing technologies. Yet, bio-logging is more than a mere catalogue of tools and techniques. The possibility to obtain an uninterrupted flow of information pertaining to both the activity and physiology of animal and its immediate, physical surroundings revolutionised the way we consider several fields in biology. We could draw a parallel with the field of genetics and how it evolved from Gregor Mendel crossing variety of peas to the advanced technologies of molecular sequencing. Similarly, the ecologist with its notebook possesses now a suite of approaches to examine animals living freely in their environment. In this context, bio-logging applications ranges from physiological investigations to the comprehension of the functioning of ecosystems, by relating a change in physical parameters of the environment to a change in the behaviour of both a predator and its prey, at the same spatial and temporal scales (Ropert-Coudert et al., 2009a).

1.2. Bio-logging in the scientific community

The word bio-logging was coined at the occasion of the first symposium about the topic held in 2003 in Tokyo, Japan. Over the past decade, three additional symposia took place: Saint Andrews (Scotland) in 2005, Pacific Grove (USA) in 2008, and Hobart (Tasmania) in 2011. The next bio-logging symposium will be organized in France and is tentatively scheduled for Strasbourg in September 2014. The number of manufacturers has steadily increased since the inception of Wildlife Computers (USA) in 1986, the first – to the best of our knowledge – bio-logging company ever. Nowadays, the core of the bio-logging production is concentrated in the North America and Japan (Ropert-Coudert et al., 2009b), but emerging companies in the UK (CTL), Iceland (Star-Oddi) or Italy (Technosmart) are gaining worldwide momentum (Table 1). A non-negligible proportion (a rough estimate of 20%) of bio-logging devices is still produced in research institutions, the so-called custom-made bio-loggers, and is thus accessible only through collaborations between researchers. In Europe, for example, research-driven developments are found in the Sea Mammal

Table 1: A non exhaustive list of the most-used bio-loggers together with their weights and the sensors they include, as well as the name of the manufacturers.

Model	Weight (g)	Sensors	Manufacturers
Mk 15	2.5	Light, wet or dry status	British Antarctic Survey, UK
Cefas G5	2.7	Depth, temperature	Cefas technology Ltd, UK
DST bird	1.7	Temperature, light	Star-Oddi, Iceland
DST magnetic	19	Depth, temperature, magnetometer, tilt	
ORI400-D3GT	9	Depth, temperature, acceleration	Little Leonardo, Japan
W1000-3MPD3GT	130	Depth, temperature, speed, acceleration, magnetometer	
W400-ECG	57	ECG	
DSL400-VDT II	82	Depth, temperature, image	
GiPSy I	22	GPS	TechnoSmart, Italy
CatTraQ	22	GPS	Mr. Lee, USA
Mk9	30	Depth, temperature, light, acceleration, magnetometer	Wildlife Computers, USA
SPLASH10-F-400	225	Depth, temperature, light, GPS, Argos (data transmission)	
DTAG	300	Depth, audio, pitch, roll, heading	Woods Hole Oceangraphic Institution, USA
SRDL tag	370	Depth, temperature, speed, Argos (data transmission)	Sea Mammal Research Unit, UK
CTD tag	545	Depth, temperature, conductivity	
GPS Phone tag	370	Depth, temperature, GPS, GMS (data transmission)	
Daily Diary	42	Depth, temperature, light, speed, acceleration, magnetometer	Swansea University, UK

Research Unit of the University of St. Andrews, which organized the 2nd bio-logging symposium. In France, the only openly declared bio-logging development team is found at the Institut Pluridisciplinaire Hubert Curien in Strasbourg. The next big step for the bio-logging community will be to form a society so as to reach an official status and help structuring the community. Bio-logging is especially expected to play an important role in the forthcoming decade regarding conservation issues and will represent a crucial tool to assess large vertebrate species distribution and links between the physical environment and the biological response of animals to its variation (see Cooke, 2008).

2. Overview of bio-logging applications

2.1. Reconstructing the movement and feeding behaviour

The ancestors of all bio-loggers are probably time-depth-recorders, commonly referred to as TDR in several instances. These devices record hydrostatic pressure according to time so as to reconstruct diving activity of sea animals. Oddly, the very first incarnation of a TDR, which was attached to a freely-diving Weddell seal *Leptonychotes weddelli*, consisted in coupling a kitchen timer with a pressure transducer (Kooyman, 1965; 1966). Subsequent devices also functioned on a mechanical basis, such as miniature pencils that were animated by pressure changes and drew the profiles of dives onto a miniature paper (e.g. Naito et al., 1990). The emergence of solid-state memories put an end to this era of clever handcrafting. Nowadays, TDR can weigh as less as 2.7g and are able to capture depth and temperature data every second for around 10 days. When associated with GPS, they provide localisation onto both the horizontal and vertical dimensions, on a large range of species.

Originally, TDR delivered only a 2D view of the diving activity (depth according to time) but progresses in behaviour reconstruction came from the utilisation of accelerometers. Accelerometers record gravity-related and dynamic acceleration signals and can be used to provide specific information about the movements of the body, such as walking gait (e.g. Halsey et al., 2008) or head-jerking (e.g. Viviant et al., 2010). The potential of accelerometers to reconstruct time budget activity was demonstrated in several instances (e.g. Yoda et al., 1999; Ropert-Coudert et al., 2004a; Watanabe et al., 2005). The addition of gyroscopes and magnetometers makes it possible to reconstruct the precise path of animals in the three dimensions. This approach, called "dead reckoning" (Wilson et al., 1991), is very prone to making substantial errors. For example, a Weddell seal diving for ca. 17mn would accumulate an error in its position calculated *via* dead reckoning of nearly 100m over this period (see figure 5a in Mitani et al., 2003). While methods exist to take this error into account (Mitani et al., 2003), dead reckoning is yet to be implemented at time scales longer than a few days. Anyway, the precision of tracking techniques thanks to GPS development makes it unlikely that dead reckoning will become a major approach. Small body movements, such as limb movements (Wilson and Liebsch, 2003), can also be finely reconstructed using Hall sensors, i.e. sensors measuring the intensity of the magnetic field. In this case, a magnet placed on one mandibular plate facing a Hall sensor glued onto the other mandibular plate (figure 1) allows researchers to determine when a prey has been swallowed and, following a proper calibration, the size and type of prey (Wilson et al., 2002; Ropert-Coudert et al., 2004b).

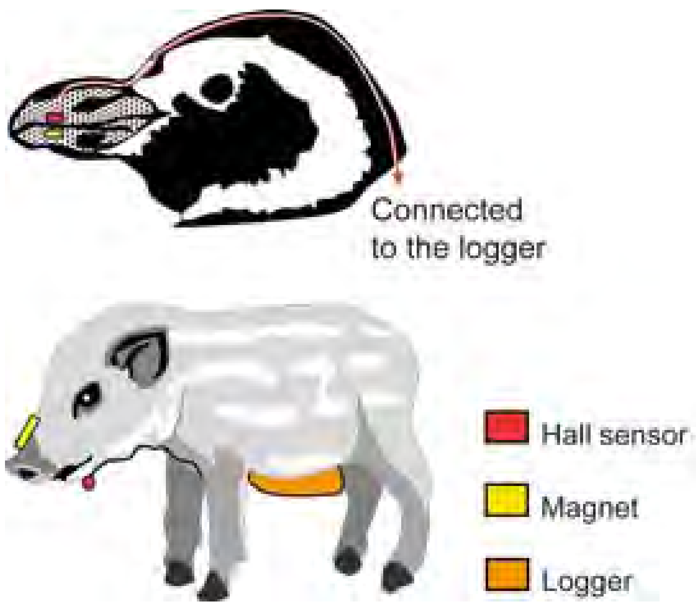

Figure 1: Schematic representation of the jaw movement recorder on a gentoo penguin *Pygoscelis papua* (top) and a young wild boar *Sus scrofa* (bottom). A magnet and a Hall sensor, sensitive to the strength of the magnetic field are placed on the two mandibles, facing each other. When the mouth opens the Hall sensor senses a reduction in the intensity of the magnetic field and sends this information via a cable to the bio-logger attached on the body.

Finally, in the context of assessing animal movements on a world-wide scale, the two major developments of the recent decades feature the advent of GLS (global location sensors) and of GPS (global positioning system). Global location sensors are miniaturised units that store light measurements at regular intervals, from which position can be estimated (using day length and noon time). Initially described by Wilson et al. (1992a), this method revolutionised migration studies because devices are particularly small (around 1g), cheap, and are able to record data up to several years. They can therefore be deployed year-round on a wide range of individuals and species (Fort et al., in press). Miniaturised GPS (the smallest ones currently weigh 5g or less) usually have shorter recording times yet far higher spatial resolution than GLS (a few meters versus a few tens of km). Their generalised use triggered a quantum leap in the spatial ecology of free-ranging animals (Ryan et al., 2004)

2.2. Reconstructing the internal temperature and heat flux

Animal-borne bio-loggers also benefited physiological studies as these bio-loggers allowed researchers to investigate internal adjustments to the constraints of, for example, experiencing extremely low temperatures (Gilbert et al., 2008; Eichhorn et al., 2011). These feats cannot be realized in the confines of a laboratory. Reduced core temperature in the body of deep divers like the king penguins *Aptenodytes patagonicus* shed a new light on the physiological mechanisms involved in energy savings at great depths (e.g. Handrich et al., 1997). In parallel to the externally-attached bio-loggers that recorded mandibular activity (see above), measurements of temperature in the stomach (Wilson et al., 1992b; Grémillet and Plos, 1994) or the oesophagus of endotherms (Ancel et al., 1997; Ropert-Coudert et al., 2001) also permitted to explore when these animals fed onto their exothermic prey as their swallowing induced a drop in the temperature (see figure 2 and additional discussions around the principle and the limitations of this method in Hedd et al., 1995; Ropert-Coudert et al., 2006a). Heat flux measurement bio-loggers may also be used to study homeothermy in animals swimming in cold waters (e.g. Willis and Horning, 2005).

2.3. Reconstructing the heart effort: ECG vs. heart rate

One challenge in ecophysiology is to determine energy expenditures of free-ranging animals. Field methods based on doubly-labelled water exist but these are long-term methods that integrate the energy expended over a period of few days (Speakman, 1997). Further to the point, these methods require multiple capture and handling, which are not always easy to implement in the field, especially for shy and sensitive species. Cormorants, for example, respond to handling with intense overheating. Last but not least,

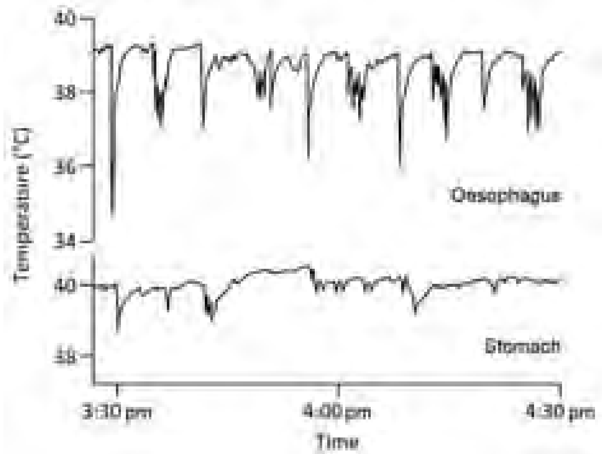

Figure 2: Two temperature signals (°C) recorded by sensors placed in the upper part of the oesophagous (top) and in the stomach (bottom) of an Adélie penguin *Pygoscelis adeliae* fed with cold food items. Each ingestion is visualised as a sudden drop in the temperature, followed by a slow recovery.

the doubly-labelled water method is expensive and implies a laboratory specifically equipped with isotope analysis facilities. In contrast, the measurement of heart rate can give an idea of the energy expended, as heart rates are linked with metabolic rates (Nolet et al., 1992; Green et al., 2001; Weimerskirch et al., 2002). Although the shape of the relationship is often unclear (Froget et al., 2002; Ward et al., 2002; McPhee et al., 2003), measuring heart rate still enables the estimation of the effort allocated to basal versus non-basal (e.g. locomotor) activities.

Among the bio-logging approaches for measuring heart rate, two techniques have emerged: *i*) heart rate recorders (HRR) that detect the heart beat and store in their memory the interval between each heartbeat or the number of heart beats per certain time period; *ii*) electrocardiogram recorders (ECGR) that monitor and store the complete electric signals allowing to access the complete PQRS profile of a heartbeat. Both systems measure the electrical activity of the heart transmitted *via* 2 or 3 electrodes placed in different parts of an animal's body. HRR have an extended autonomy since they only count intervals (Grémillet et al., 2005) but are prone to error because the ability to distinguish heartbeats from electric noise due to muscular activity depends solely on an onboard algorithm. In contrast, ECGR requires a processing of the signal but this ensures that only heartbeats are counted (Ropert-Coudert et al., 2006b; 2009c). However, commercially available ECGR have limited autonomy.

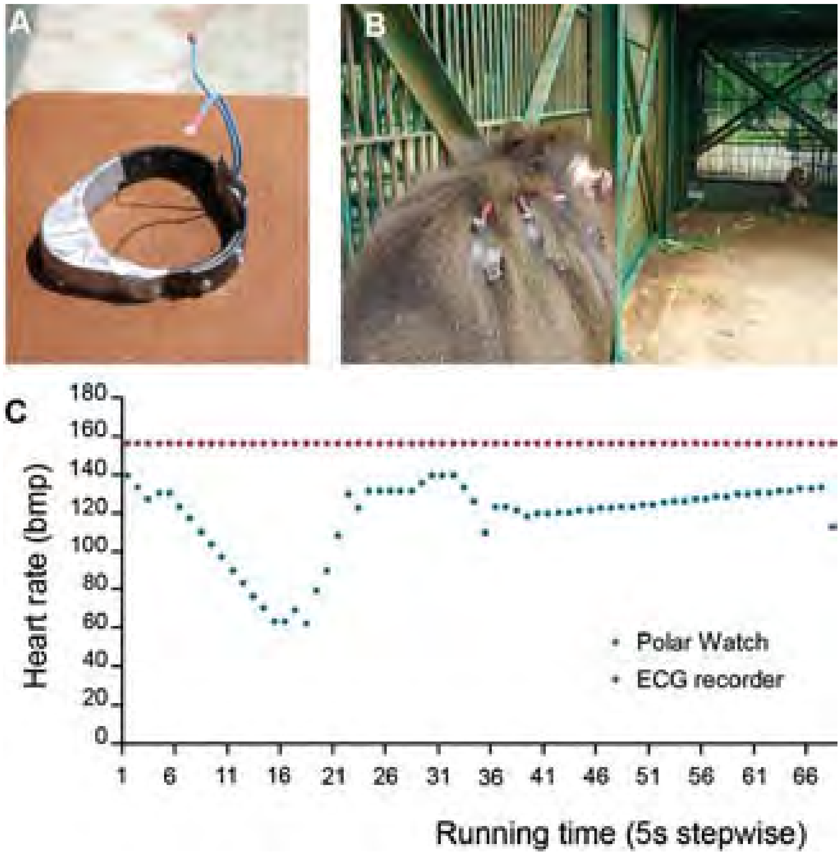

Figure 3: Recordings of heart rate on a captive mandrill *Mandrillus sphinx*. A. Photograph of the collar where devices are attached and the electrodes protruding from it. B. Collar mounted on the mandrill with the electrodes plugged on the skin and secured by bolts. C. A comparison of the heart rate recorded by two different devices: a heart rate counter (Polar Watch, blue) and an electrocardiogram (ECG recorder, red). The latter allows the user to visualize each heart beat as a PQRS complex and is thus much more reliable than heart rate directly given by the counter (calculated via an internal algorythm to which the user generally cannot access). The heart rate given by the counter shows large variation that are absent on the signals derived from the ECG. © Jacques-Olivier Fortrat.

The comparison of the heart rate signals of a sleeping mandrill *Mandrillus sphinx* directly derived from a commercially-available heart rate monitor (© Polar Electro, France) and the one calculated from an ECGR (Little Leonardo, Japan) illustrates well the risk of applying tools that are developed for a specific use (here, the Polar Watch is intended for measuring heart rate during human exercise) onto an animal model without prior calibration work (figure 3). The need to reduce the risk of storing electromyograms generally leads researchers to implant the HRR in the body, while ECGR can either be implanted or externally attached. Implantation is not trivial as it involves anaesthesia and surgery, with all the associated risks, and is not always easy to perform in the field (see Green et al., 2004; Beaulieu et al., 2010).

2.4. Viewing the environment: image data logger

Data contained in bio-loggers are used to reconstruct the activity and, in some cases, the environment in which the animals move. But the dream of all users is to be able to visualise directly what the animals are seeing. Images, if they do not give access to physiological information *per se*, are a smart and informative way of studying behaviour. Images are also attractive to a large audience as they do not always require specific knowledge to be interpreted. As communication towards the public becomes paramount to Science, this is a non negligible asset for bio-logging approaches that use digital-still picture recorders or even video recorders. The National Geographic Crittercam project was a pioneer in merging the scientific community with common people. However, their usefulness to answer scientific questions was often questioned. Digital-still cameras take images following a definite sampling interval which is not always adequate for short time events like prey capture.

Yet, these techniques can provide unravelled insights into prey identification (figure 4, see also Davis et al., 1999; Watanabe et al., 2006), prey density (Watanabe et al., 2003), group behaviour (Takahashi et al., 2004a; Rutz et al., 2007) or the biomechanics of flight (Gillies et al., 2011). Video recording systems have limited autonomy and are still rather bulky to be used without the risk of impairing the performances and health of some animal models (see the bulkiness of a video recorder mounted on an emperor penguin in the figure 1 from Ponganis et al., 2000). Recent advances in miniaturisation allowed for these devices to be placed on the head of a flying seabird (Sakamoto et al., 2009). In an applied context, it has been recently proposed to use newly-developed, highly miniaturised digital-still picture recorders mounted on seabirds to monitor pirates fishing boat (Grémillet et al., 2010).

2.5. Reconstructing the environment: animals as bio-platforms

The pioneers of bio-logging soon realised that this technology not only allowed the study of animals in their natural surroundings, but also to access their biotic and abiotic environment. Especially in the oceans, where sampling through the water column is impossible from satellites and expensive from research vessels, this approach led to remarkable advances. As soon as time-depth-recorders were coupled with positioning devices and temperature sensors, the thermal structure of water masses could be assessed. This was first conducted in Antarctica by Wilson et al. (1994), which used penguins equipped with data loggers to map thermal gradients across the 100m of the Maxwell Bay. Not only did they assess this abiotic parameter, but they also cross-checked this information with an estimation of krill biomass in this water mass, which was based upon the predatory performance of the birds. This approach was revolutionary. Yet, temperature measurements were too coarse to be adequate for proper oceanography work. It is only a decade later that seabirds were equipped with loggers measuring ocean temperature to 0.005K and depth to 0.06m, values accurate enough to track the vertical movements of the thermocline off Scotland in the North Sea (Daunt et al., 2003). However, this approach was then only used to investigate areas that had been already studied, and had been sampled using conventional, ship-based surveys.

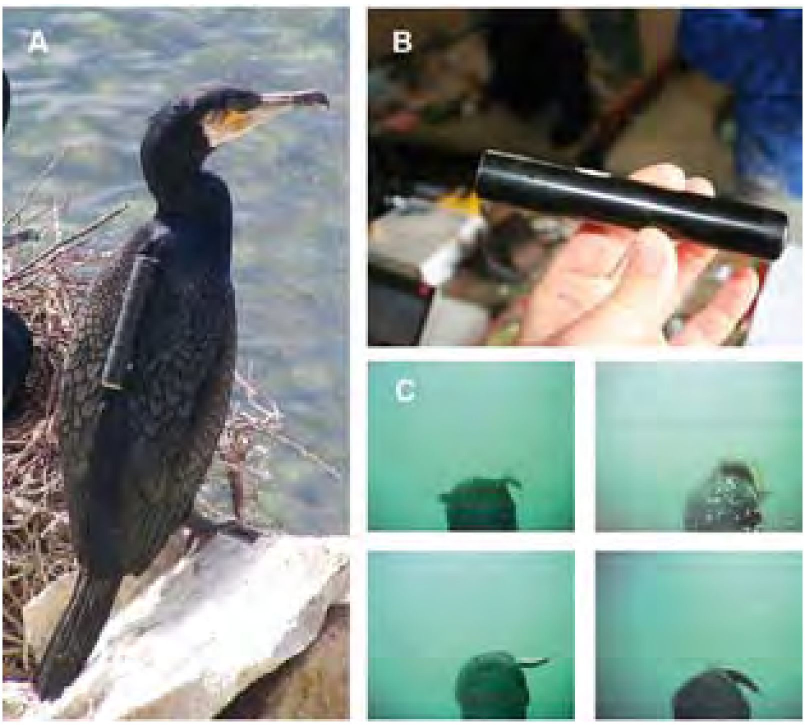

Figure 4: Image data loggers. A. A digitial-still-picture logger (Little Leonardo, Japan) mounted on a great cormorant *Phalacrocorax carbo* in Greenland (left, © David Grémillet) together with a view of the logger itself (B) and four examples of pictures taken by the logger (C). The examples show fish prey caught in the beak of the cormorant.

The next step consisted in using free-ranging marine animals fitted with bio-loggers to sample unknown areas. For instance, Charrassin et al. (2002) used temperature data collected by diving king penguins to identify a previously-unknown water mass off Kerguelen in the Southern Ocean. However, operational oceanography requires real-time assessments of biotic and abiotic parameters, for instance to parameterise models of ocean circulation and climatic processes (IV, 1). This was not possible using ancient archival tags fitted to marine predators, since those had to be recovered to download the data, sometimes weeks or months after the actual measurement. Such problem was solved by the use of a system integrating bio-physical sensors of the environment (e.g. water colour, temperature, salinity) and sensors of the animal's movements (3D acceleration, depth and speed) with the Argos positioning and transmission system. Such tools are large, require substantial battery power, and can only be deployed on large marine mammals for the time being, in particular elephant seals (*Mirounga leonina*). However, they allowed a major step forward because elephant seals cruise the Southern Ocean in areas that are beyond the reach of satellite or vessel-based oceanography, especially in the marginal ice zone off Antarctica and at depths of more than 1000m (Charrassin et al., 2008). From these areas, devices fitted to these large, record-breaking divers can send new data which are now being routinely integrated into ocean physics models (Roquet et al., 2011).

2.6. Multi-information sensors: the special case of accelerometry

A single parameter may not always be sufficient to address a scientific question, such as in the case of the dead reckoning technique that we mentioned earlier (section 2.1). However, the use of multiple sensors is not always possible since it generally leads to an increase in the bulkiness of the devices. Fortunately, accelerometry can be used to derive more information than only the posture or the activity of animals. For example, with sensitive accelerometers, it is possible to detect the faint signal of the heart rate in the movements of the cloacae of a bird and thus address physiological questions without the need for electrodes and/or implanted materials (Wilson et al., 2004). In addition, since a rough 70% estimate of the energy is expended through movements, overall dynamic body acceleration (ODBA) or partial dynamic body acceleration (PDBA), derived from 3-axes or 2-axes accelerometers, respectively, was proposed as an index of energy expenditures (Wilson et al., 2006). ODBA and PDBA are indeed significantly related to oxygen consumption in a variety of species, and both offer a good proxy of metabolic activity when combined with heart rate loggers (Halsey et al., 2008). Apart from accessing physiological parameters, these sensors can also be used to infer prey availability in the environment. Changes in wing beat frequency and amplitude are increasingly used to infer prey encounter in birds (Ropert-Coudert et al., 2006b), while detection of head jerking movement are related to prey capture in marine mammals (Suzuki et al., 2009; Viviant et al., 2010).

3. The road to bio-logging is paved with good intentions but…

3.1. The standard bio-logging trade-off

Increasing the life-time of a bio-logger while keeping the same level of performances leads to the following paradox. On the one hand, the amount of information stored is increased, and consequently the memory capacity has to increase too; on the other hand, the energy required to power the electronic circuit is increased, and so should be the battery size and weight in order to address this extra demand. Based on the power consumption of a unit, it is possible to adapt batteries of different capacities to the devices in order to adjust the working-time to the specific needs of a study. However, a longer working-time means larger and heavier batteries and bio-loggers, which may have an impact on the health of the species targeted or even become inappropriate (I, 2). This balance between small units with a lesser impact on the animal but reduced life time, and larger devices with enhanced functionalities but restrictions on their applicability, is a major problem seriously dealt with by the bio-logging community *i*) for ethical reasons, and *ii*) to ensure that the data collected are reliable and are as close to the norm as possible (Ropert-Coudert et al., 2007).

Regarding the impact of bio-logger, one must be aware that animals are generally shaped to optimise their movement through a medium. Swimmers are hydrodynamically featured, while flying animals present a specific adaptations to reduce their body mass. Thus, any externally-attached item may impair these features and lead to an increase in energy expended or a change in behaviour. In parallel, we already mentioned the negative consequences of implanting bio-loggers. Guidelines are regularly produced to reduce the negative impact of bio-loggers (Casper, 2009). Bio-loggers, for example, should weigh less than 3% of the body mass of flying birds (Phillips et al., 2003) and less than 4-5% of the cross-section of the animal (Bannasch et al., 1994).

Despite these guidelines, we believe that the scientific community should move forward to adopt a common code of conduct. Indeed, the bio-logging community is very mindful about the need to reduce the impact of devices, but newcomers may not always be aware of guidelines specifically designed for bio-logger deployments (see above). In some instances, referees are not aware of them and accept papers that present ethical concerns or which results are questionable due to the negative influence of a bulky device on the performances of the animals. Which institution could be in charge of ensuring that the appropriate guidelines are followed? Some scientific journals have taken the lead in addressing this problem: for example, Animal Behaviour has very strict ethics regulations and ask the authors to address them before submission to peer review. The pressure to produce attractive results could, however, hinder these efforts as it sometimes pushes researchers to emphasise outputs against rigor (see Ropert-Coudert et al., 2007). Conversely, enforcements of strict rules would also be detrimental without consideration of the benefits that overstepping them could bring in terms of new scientific results.

3.2. Beyond sensors and devices: homogenising analyses and sharing data

Originally, each research group using bio-logging approaches developed its own method for analysing the data generated by bio-loggers. This led to the emergence of several analytical programming codes that tackled the same question and therefore, to a divergence in the way bio-logging data were processed. For example, the bottom phase of a dive can be defined in several different manners, leading to values that are not comparable from one study to another. The trend of diversifying the analytical methods is also enhanced by the presence of free software like R that allows users to create and disseminate their own codes and thus their own definitions for various parameters. In addition, the possibility offered by most bio-loggers of selecting the frequency at which the sampling is done also leads to diversification and renders comparisons across data sets difficult. In physics, the "sampling theorem" states that the sampling frequency must be at least twice that of the signal's highest component frequency (for a periodic signal) to avoid aliasing. Similarly, biologists suggested that the sampling interval should not represent more than 10% of the duration of the biological event that one wishes to measure (e.g. the lowest sampling frequency to measure a 600sec dive of a Weddell seal is 60sec, Boyd et al., 1993; Wilson et al., 1995). Not adopting a proper sampling protocol may lead to misinterpretation of the data and false biological conclusions (Ropert-Coudert and Wilson, 2004).

Recently, the question has become a topic of reflexion on the occasion of various workshops. Can we (and should we) homogenise bio-logging data analysis? The difficulty to define the best practice in that case is twofold. First, devices always evolve and become more efficient or collect new types of data. Consequently new analytical methods are required to handle these novelties. Secondly, the analytical method depends upon the questions sought. In that sense, the currently best practice would not stay best for very long. Yet, we need to be able to compare datasets taken in different locations, time and using different means, especially if we are to tackle large-scale questions. Methods like down-sampling, although necessarily frustrating, are keys to address such issues. We strongly advocate for working groups to explore paths for the homogenisation of analytical procedures within the framework of, for example, the Expert Group in Birds and Marine Mammals of the Scientific Committee for Antarctic Research (SCAR), or the newly-formed group of experts in accelerometry that was constituted on the last bio-logging symposium in Hobart.

In addition to this issue, the use and share of data from bio-logging must be optimised. A whole book could be filled with the issue of data sharing, but only the surface will be scratched here. The million of data points that are now routinely recorded by data loggers and the multiplicity of the research teams using such an approach make it necessary to centralise, archive, and ultimately share the data. Some researchers had been collecting bio-logging information over several decades and onto a large range of individuals and species. Upon retirement, their data would be lost if no system stores them. This is only recently that specific data repository have emerged. The tendecy is now to multiply storage points, each scientific society recognizing the need for a database on their specific topic. For example, marine researchers studying the localisation and diving activity of polar top predators can store their data into the database managed by the SCAR (SCAR-marBIN and Antabif) that are themselves linked to marine databases at a larger scale (OBIS, SeaWiFS, etc.). This multiplication and cross-sharing of datasets among databases, while duplicating the work, guarantee the permanence of a dataset as it will still be available even if one database is closed. An incentive to sharing the data is found in the recent effort to consider data sharing as a genuine publication, associating a DOI to a data set. As such, institutions evaluating a researcher's output can value his/her effort towards the scientific community through this marker.

3.3. Bio-logging: an academic and commercial endeavour

Efficient bio-logging equipment is generally achieved through a close collaboration between engineers and users. However, research institutions able to combine both expertises under the same roof are scarce. In some privileged situations, an academic collaboration can be developed between universities so as to link a department of biology and an engineering department for example. The highest technical sophistication can then be attained and complex and specific questions be answered. Once a prototype is created, engineers face more practical duties that may be less intellectually satisfying. Among those, the issue of proper conditioning and packaging of the device is critical. Most dysfunctions of bio-loggers are due to practical packaging problems. Solving these problems requires a multidisciplinary and complex engineering approach. Once the equipment has finally been validated, biologists would request a large number of units and this is precisely when academic systems reach their limits. Indeed, academic bodies are (and probably should) not be involved into mass production as this would mean adopting an industrial approach to bio-loggers production. Industrial production implies that electronics hardware, software, connectic systems and batteries, circuit design and protection, casing and packaging, tests and validation, are all included at once in the reflexion process. Additionally at each stage of development, costs are balanced and they influence decisions at the next stage. Industries usually aim at producing the best device according to the cost it represents for them; and this is generally decided with consideration of the market, the number of potential customers and the most reasonable price per unit. Real and viable situations generally lay between these two positions. Subcontracting industrial fabrication could be an alternative for academic developers. Academic engineers and/or researchers could also create a start-up company based on what they developed to initially address their scientific needs. However, this involves an optimal knowledge of the scientific and technical need, as well as of the practical problems that may be encountered in the field while using the equipment. In a nutshell, everything reverts to the following question: is the demand originating from users asking for specific developments (greater performance, new sensors…) or from the engineers anticipating the application of new technologies? Both stimulations are probably necessary to draw an ambitious but realistic product specification.

4. Where do we go from here?

4.1. Going toward large-scale deployment

For decades, the paucity of manufacturers, the expensive price of bio-loggers, their restricted memory or battery capacity, as well as the lack of adapted analytical tools precluded the deployment of numerous units at a time. Thanks to technological advances, such as those taking place in the mobile phone industry, some cheap, low consumption and consequently small bio-loggers have started to appear on the market. With these, large-scale deployments have become achievable. While occasionally dozen of devices had been deployed simultaneously to explore cooperative diving (Takahashi et al., 2004b), the first large-scale deployments, in both space and time, originated through programs like the Tagging of Pacific Pelagics (Topp, Block et al., 2003, see also http://www.topp.org/). Since the inception of the Topp programs, thousands of tags have been attached to 22 top predator species in the Pacific, including whales, sharks, sea turtles, seabirds, pinnipeds and even squids. Mass production of devices is now a reality: it allows researchers to work at unprecedented spatial scales and on entire populations of studied animals. In this field, the United Kingdom has taken a huge step forward. For example, the long-life, minute geolocators developed by the British Antarctic Survey are deployed on a worldwide scale (e.g. Conklin et al. 2010). Recently, mass-production of GPS for mobile phone also created an alternative market where cheap GPS can be purchased by researchers who can re-conditioned them specifically to their needs. As an illustration of this, the IPHC bio-logging unit is modifying commercially-available GPS units (Cat Traq from Perthold Inc., http://www.mr-lee-catcam.de/ct_index_en.htm) to make them suitable for use on wild animals. However, there is a negative side to this large-scale enthusiasm: cheap devices do not always meet the usual scientific criteria. Lesser reliability or lower degree of technical information must be balanced with the benefits that can arise from the use of these mass-production bio-loggers. In other words, caution in the use of cheap devices must be taken to avoid impacting scientific excellence. Thorough calibration must be a premise to large-scale deployments.

4.2. Importance of multiple sensors

As evoked briefly earlier in this chapter, the use of multiple sensors – when applicable – offers an added value by providing a much complete picture of the behaviour and physiology of the animals in their environment. The combination of simple sensors (e.g. pressure sensor and temperature sensor) became a standard in even the simplest data loggers, but genuinely multi-sensor loggers are still few. Among those, it is worth mentioning the "daily diary" unit developed by Prof. Rory Wilson at the University of Swansea. Despite their relatively small size ranging between 21 and 90g according to the size of animal, these bio-loggers can contain up to 14 different channels of both slow and fast sampling sensors working simultaneously (Wilson et al., 2008). Apart from the daily diary unit, multi-sensing devices, either developed by research teams or commercially available (Wildlife Computers, Little Leonardo, Greeneridge Science, etc.), are used in large body sized models, e.g. fin whales *Balaenoptera physalus* (Goldboegen et al., 2006). To extend the applicability of multi-sensing devices to smaller animals, special developments are needed (I, 2); for example, a drastic reduction in the consumption is a pre-requisite to a generalisation of multi-sensing to species smaller than a 1-2 kg animal. In addition, new chemical sensors to detect for example the level of oxygen in the water or the blood will pave the way for new generations of multi-sensing bio-loggers with new requirements and constraints for the developers. Here, a distinction must be made depending on the acquisition rates of these new sensors. The deployment of sensors for quasi-static parameters for which the sampling interval is equal or longer than 1s (e.g. temperature, light, pressure…) would not cause any trouble as transducers use low power and the volume of data is small. However, the use of sensors for medium speed parameters sampled typically between 10 and 100Hz (e.g. accelerometers, gyroscopes, etc.) requires larger memory volume and greater energy to store the data. Even stronger difficulties are faced for sensors that acquire high speed parameters (more than 100Hz) like electrocardiograms, electromyograms, or electroencephalograms. Numerous technical problems occur, and a special electronic architecture is needed to manage the high volume of memory, high speed communication for data transfer, and so on.

With the million of data points that the daily diary units can generate, the next challenge will be to develop a software able to handle, display and summarise the complex information delivered by the next generation of bio-loggers. Prof. Wilson thus invested an important amount of energy, resources and time in developing such a tool and did it in such a way that its utilisation can reach a larger public than the scientific community alone (Wilson et al., 2008, http://www.swan.ac.uk/biosci/research/smart/smartsoftware/). The software allows users to interpret the data from the bio-loggers so as to truly reconstruct behaviour and visualise it. For example, data points from the magnetometer, gyroscope, accelerometer and altitude sensors are combined and the result on the screen is an albatross (a computer graphic one, of course) flying in three dimensions following the exact paths that the original albatross flew. Beyond the example of the daily diary, visualisation software to accommodate complex and large datasets and display them in a pleasant and efficient manner is becoming increasingly available. The statistical free software R is of course powerful and readily accessible but its lack of user-friendliness may sometimes limit its popularity for complex analyses and representations. Alternatives to R are numerous and we can only mention Igor Wavemetrics, which was recurrently presented at the last bio-logging symposium (http://www.wavemetrics.com/).

4.3. Combining the best of biotelemetry and bio-logging

Biotelemetry – at least in theory – clearly has its advantages, especially as long as securing data is concerned. However, real-time data transmission is practically hampered by numerous factors leading to a temporary interruption in communication, which in turn means a definite loss of measurements (Vincent et al., 2002; Costa et al., 2010). These blank periods are generally due to technical limitations (e.g. signal attenuation, wave's absorption by the environment, electromagnetic interferences, etc.) and to the behaviour of the animal to which the transmitter is attached (e.g. relative position of body and antenna, immersion in water or in a burrow, etc.). In comparison, bio-logging seems the perfect solution. Yet it suffers from an important drawback: the bio-logger has to be connected back to a computer at the end of the experiment to retrieve the data, which means that the animal has to be still alive, re-localised, re-captured and should still be carrying a bio-logger that is still functioning! In other word, deploying a bio-logger represents a binary game: if only one point goes wrong in the chain, no data are collected.

Obviously, combining the capabilities of the two methods seems to be the solution. An ideal device would record permanently the data in an embedded memory, and would then transmit them regularly to a base station. Of course, this basic principle needs to be adjusted to each experimental situation. Data may be transferred following a fixed schedule, for instance when an animal returns to a fixed location in space and time. As a consequence this would only require a single base station installed within radio range of such a site where the animal is known to be found at regular interval, and with a bidirectional connection between the logger and the station. The base station would be filled gradually with data from the logger, and be downloaded by the user when needed. If the animal disappears only the data collected after the last transfer with the base station are lost. Alternatively, the base station can interrogate the environment at fixed schedules or be triggered manually to search for a telemetric logger within its reception range (see the approach developed by the University of Amsterdam, Shamoun-Baranes et al., 2011). The reverse strategy consists in asking the telemetric logger to regularly scan the radio-frequency environment, in order to search for a base station. In this case, scattering numerous base stations in a given experimental area would enhance the success rate of data transfer. These stations can also communicate between each other to optimise data organization and synchronisation. Additionally, each base station can communicate with a large number of telemetric loggers. The last step in this concept consists in bio-loggers able to communicate not only with base stations, but also among themselves, leading to a genuine network of communicating devices. Data would then be shared with all the loggers coming within communication range and then transferred to a base station when one logger is close to it. A non-negligible side aspect of such an approach is the possibility to investigate proximity between animals, including time, duration and possibly distance of encounters. While theoretically attractive, a fair amount of development has to be done to reach this grand challenge. Both advances in electronics and data communication protocols are required. Progresses in theoretical studies over software that could be able to manage such complex sets of interactions are paramount to the future success of these bio-logging networks and cannot involve only one type of institutions.

5. Conclusion

Bio-logging has gone through several steps from mechanical to digital, and from bulkiness to miniaturisation. The field is now moving towards globalisation and large scale coverage. In the marine realm, bio-logging coupled to automatic identification and weighing systems such as those that exist in the Antarctic could serve as a basis for long term monitoring programs. Such observatories would thus act in parallel with weather or oceanographic stations to deliver data on Antarctic biodiversity. This concept can be extended to the terrestrial realm with a network of sensing nodes monitoring the state of terrestrial ecosystems over time. With the rapid modifications affecting all ecosystems on Earth, monitoring programs such as these are urgently needed. The diversification of the data collected, the increase in the temporal coverage and accessibility of bio-logged data, and the possibility for large number of units to be deployed in a given environment concur to promote bio-logging as the key approach for ecological sciences in the future.

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Sensors for ecology

Towards integrated knowledge of ecosystems

Key features

- An overview of sensors in the field of animal behaviour and physiology, biodiversity and ecosystem.
- Several case studies of integrated sensor platforms in terrestrial and aquatic environments for observational and experimental research.
- Presentation of new applications and challenges in relation with remote sensing, acoustic sensors, animal-borne sensors, and chemical sensors.

Ecological sciences deal with the way organisms interact with one another and their environment. Using sensors to measure various physical and biological characteristics has been a common activity since long ago. However the advent of more accurate technologies and increasing computing capacities demand a better combination of information collected by sensors on multiple spatial, temporal and biological scales.

This book provides an overview of current sensors for ecology and makes a strong case for deploying integrated sensor platforms. By covering technological challenges as well as the variety of practical ecological applications, this text is meant to be an invaluable resource for students, researchers and engineers in ecological sciences.

This book benefited from the Centre National de la Recherche Scientifique (CNRS) funds, and includes 16 contributions by leading experts in french laboratories.

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