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Title:	Wild state secrets: ultra-sensitive measurement of micro-movement can reveal internal processes in animals
Year:	2014
Journal:	Frontiers in Ecology and the Environment
Volume:	12
Issue:	10
Pages:	582-587
URL:	http://hdl.handle.net/1959.3/391479
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Wild state secrets: ultra-sensitive measurement of micro-movement can reveal internal processes in animals.

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- *'… man and animals, express the same state of mind by the same movements'. Charles Darwin et al. [orig. 1872] (Darwin, 1998)*

Assessment of animal internal 'state', or system operational status, which includes hormonal, disease, nutritional and affective states, is normally considered the province of laboratory work, precluding its easy determination in wild animals. However, we show that accelerometers attached externally to animals as diverse as elephants, cockroaches and humans display consistent signal differences in animal micro-movement that is indicative of state. Accelerometers, originally incorporated into tags to elucidate the behaviour of wild animals, thus have huge potential for explaining animal actions which are considered to be a response stemming from the interplay of animal internal state and environment. Cognisance of this may help wildlife managers understand how state is linked to behaviour and movement and thus give better understanding of issues ranging from how animals deal with new roads to the spread of diseases such as avian influenza.

In a nutshell:

- Recording devices attached to wild animals have already allowed researchers remarkable insights into animal ecology, with accelerometers being particularly useful for determination of behavior
- Accelerometers now show that animal internal state, normally only accessible via laboratory tests, is manifest in body micro-movements
- Since behavior is derived from animal state and environment, the use of accelerometers in wild animals should allow wildlife practitioners to better understand and predict behavior

How animals position themselves and behave within the environment, is a powerful descriptor of the role they play in their ecosystems. This is because the animal's use of space determines those ecosystem elements to which it is exposed, while its behavior influences the elements within that space (Lima & Zollner, 1996). This has been the essence behind drives to develop methods which define where wild animals operate within the environment, such as VHF- and satellite-telemetry (Hebblewhite & Haydon, 2010), as well as approaches for determining animal behavior, such as the use of accelerometry (Watanabe, Izawa, Kato, Ropert-Coudert, & Naito, 2005). Animal position and behavior are, however, only two interdependent elements within a critical 3-element triangle that defines animal-environment interactions. The third element is animal internal 'state' (e.g. Saarenmaa et al., 1988). The internal 'state' of an animal reflects the animal's operational status (Clark, Rager, & Calpin, 1997), incorporating components such as its nutritional, hormonal, immunological, chemical and affective states (Mendl, Paul, & Chittka, 2011). It is the interaction between state and environment that is presumed to drive observed behaviors (Duncan & Petherick, 1991) so that quantification of animal state should help us understand strategies adopted by wild animals (Nathan et al., 2008; Saarenmaa, et al., 1988). By its very nature, however, the internal state of an organism is best described by examination of the animal's internal conditions, something that requires quantitative analysis of ~~e.g.~~ physiological variables such as blood chemistry, the domain of laboratory work, rather than being anything applicable to free-living animals.

In this work we report on the potential of external animal-attached tags containing accelerometers, as novel and ultra-sensitive movement sensors, to provide field-workers with indicators of animal internal state. Development of this venture should equip scientists, resource managers and policy-makers with a critical element necessary for a more holistic understanding of why animals behave the way they do as they move through their environment.

■ Approach for teasing state from animal posture and movement

Experimental set-up

We concentrated our work on three specific instances of state; chemical, affective, and disease, on three very different animals; humans *Homo sapiens*, elephants *Loxodonta africana*, and cockroaches *Blaberus craniifer*, respectively, to highlight the broad applicability of this approach. Accelerometers, typically having a total volume of the order of 10 mm^3, and quantifying acceleration in the three spatial (orthogonal) axes, can be incorporated within animal-attached logging systems to record animal posture and the details of movement (Wilson, Shepard, & Liebsch, 2008). All our subjects were equipped with tri-axial accelerometers, either within full logging units taped to the wrists (humans – recording at 40 Hz),~~ or~~ attached in collars round the neck (elephants - recording at 320 Hz), or by affixing the sensors to the animals and streaming data to a computer through copper wires (cockroaches – recording at 1000 Hz). To study chemical state, participants in the human trials were divided into two groups; (i) 2~~3~~0 party drug users (recreational ecstasy or MDMA (Parrott, 2013)) who were not under the influence of drugs at the time of the study and (ii) 2~~3~~0 subjects that had never used drugs; both groups were asked to hold both arms out to the sides while data from wrist-attached accelerometers were recorded. To study affective state, we used two adult female elephants with walking behavior that was classified as “positive walking” where the subject was walking between two desired resources (food pile, mud wallow, or dust bathing area), without a dominance interaction occurring or “negative walking” where the subject was walking away after being displaced by the dominant female of the herd. “Positive walking” could be viewed as motivation or anticipation (generally a positive affective state) while “negative walking” could be viewed as fear or anxiety, (a negative affective state). To examine the manifestation of disease state, ~~8~~ eight healthy adult cockroaches were either kept as controls (n = 4) or infected with *Metarhizium anisopliae* (an entomopathogenic fungus (Butt, Ibrahim, Ball, & Clark, 1994)) (n = 4) and stimulated daily, as the infection progressed, to elicit an escape response by running up a 2 m trough while data from pronotum-attached accelerometers were recorded.

Identification of accelerometer signals indicative of state followed the general approach described in Shepard et al. (Shepard et al., 2008) for behavior, which advocates separating each acceleration channel into a static, posture-based component (by using a running mean), and a dynamic component, derived by subtracting the running mean values from the raw data which can be represented by vectorially summing all three axes to give the Vectorial Dynamic Acceleration (VDA) (Shepard, et al., 2008). Given the expected small difference in acceleration-derived signals in relation to state, we also used special software (GRAPPLER (cf. Grundy, Jones, Laramee, Wilson, & Shepard, 2009)), designed to allow multiple channels derived from acceleration data to be visualized in various ways. This included colour coding, to facilitate signal processing by highlighting patterns that might otherwise be concealed. Across the three studies, there were statistically significant differences in accelerometer data ($P < 0.05$) that accompanied states and state transitions in all three experiments although different features of the data signalled this for each case. For study of chemical state in humans, striking differences in movement, specifically ‘tremor’ values ((VDA (Shepard, et al., 2008)) were observed when the arms were held out horizontally, with the drug-user VDA scores being statistically greater at each time-point (Fig. 1). For affective state in elephants, the three axes of the static acceleration showed that the body posture varied according to whether the animals were in a positive or negative affective state (Fig. 2). ~~while~~ While disease state in the cockroaches, was manifest in significantly decreasing VDA values over time only in infected animals (Fig. 3). Thus, here, the 'dynamism' in each stride decreased with sickness.

Links between acceleration and state

Accelerometers in animal–attached loggers are becoming standard tools in the identification of animal behavior (Shepard, et al., 2008; Yang & Hsu, 2010), being able to quantify animal movement in a manner that cannot be mirrored by observers even when direct observation is possible. For example, Halsey et al. (Halsey, Portugal, Smith, Murn, & Wilson, 2009) measured not only the frequency of wing beats of raptors wearing accelerometers, which they could do by direct observation, but also derived metrics for energetic effort. The value of accelerometers for defining movement and micro-movement (which we define here as any movement that cannot be seen well enough to be quantified with the naked eye), stems from the physical measurement of a fundamental metric (acceleration) with high accuracy with no element of subjectivity. Accelerometers, such as the ones used in our study, are able to resolve acceleration to within 0.004 *g* at very high rates (in our case up to 1000 times per second per channel) and advances in solid-state technology will enhance this further. This explains why research is now able to examine manifestations of body micro-movement and how they relate to conditions. An example is the study by Flavel et al. (Flavel, Koch, White, & Todd, 2012), who reported how digit tremor in humans is symptomatic of Ecstasy/MDMA use. But accelerometers appropriately placed on the skin can also monitor a variety of body micro-movements, such as heart beating, which makes the body pulse after the manner of a drum (cf. Wilson et al., 2004). Thus, we predict that studies using accelerometers to document body micro-movements will become more common as accelerometers and software for their analysis become increasingly available. Certainly, our study cases, picked for their diversity, indicate that various states can be characterized by particular acceleration micro-signals.

The critical question is the extent to which accelerometer signals can code for varying states and be exclusive in this. This will only be answered with more work but the diversity of the signal should help here. Modern accelerometers measure in three orthogonal axes and can do so at rates of up to many hundreds of times per second which helps define repetitive waveforms (see e.g. Fig. 3). Each channel nominally records the sum of the static (gravity-based) and dynamic (animal movement-based) components which can be deconstructed and each of these signals from each channel can be used to calculate further derivatives. Any, and all, of these measures can be examined for variability within and between waveforms in a manner analogous to studies looking at ~~e.g.~~ heart rate variability according to lifestyle in humans for example (Thayer, Yamamoto, & Brosschot, 2010), and they can be further subject to almost infinite variability by being placed on different parts of the body. Thus, although tri-axial accelerometers only nominally measure in three axes, like the strings on a violin, the combination of factors can produce huge variation, music representing many different themes.

The issue of precisely why body micro-movements might change with state is complex and will depend on the specific state. With regard to chemical state, for example, MDMA users have reported movement problems (Parrott, 2013), with MDMA-induced 5-HT toxicity being suggested to produce motor system dysfunction (Parrott, 2013), as have cocaine users (Wilcox & Wilcox, 2009) attributed to dopaminergic preponderance from cocaine consumption. Most recently, the Flavel et al. (Flavel, et al., 2012) study showed finger tremor variation at rest and during movement, between abstinent Ecstasy/MDMA users, amphetamine users, cannabis users, and non-users; with, however, only the MDMA users and controls differing on 'tremor' during movement tasks. Similarly, our own differing patterns of arm dynamism between party drug users and non-users may be generally explained by motor disorders pointing to a movement-based manifestation of abnormal 'physical state' in drug-using populations. Thus, careful examination of micro-movement characteristics in non-clinical participants might be useful as early markers for movement disorders. In wildlife, ingestion of particular plant-based food stuffs, particularly those with toxins intended to deter their consumption (Hoy, Head, & Hall, 1998), may result in analogous deviations in micro-movements from the norm, potentially providing ecologists with equivalent metrics.

Manifestation of disease state will span conditions ranging from neurological disorders, such as Parkinson's disease and bovine spongiform encephalopathy, where atypical movement should be readily apparent using accelerometry for reasons similar to those manifest in certain chemical states (see above), and illnesses that are not specifically muscular or neurological in effect. In the latter case, however, disease also leads to generally compromised performance and increased lassitude, which we would expect to be manifest by both postural and dynamic movement changes. Certainly, our cockroaches showed both postural changes and reductions in VDA (Fig. 1) so this general framework would seem a good place to examine animal health.

Inevitably, descriptions of animal health include documentation of hormone levels, particularly where stress hormone levels are undesirably high (Lundberg, 2005). The effect of many stress hormones is to increase metabolic rate coupled with enhanced vibrancy (Lazarus & Folkman, 1984) which, in a manner similar to the tremors observed in party drug users (see above), should be manifest via accelerometry, albeit with possibly a different frequency. Hormonal state also drives affective state to an extent, and since Ecstasy/MDMA users display cortisol levels 400% higher than controls (Parrott, 2013), this may contribute to their psychomotor problems. We note though, that the two broad affective states proposed in the elephant study (Fig. 2) presumably had a neurological, rather than a hormonal, basis. The possibility that we may be able to allude to animal mental wellbeing, even if couched in terms such as 'affective state' has broad ramifications for wild animal as well as domestic animal welfare. Within human society we are generally aware of the emotional state of others by the way they walk (see e.g. http://www.biomotionlab.ca/Demos/BMLwalker.html), with posture and dynamism in the gait showing the condition. The implication is that there is some value in manifesting state because it is hard, otherwise, to relate to selection pressures for optimality in movement, which would require a very particular, constant, pattern of limb use (Sekiya, Nagasaki, Ito, & Furuna, 1997). Indeed, if this has advantages in social animals, manifestation of affective state may be less obvious in solitary species. Perversely, where state belays condition in competitive interactions within species, such as in male-male duels, we might expect selection pressure for reduced signs of 'weakness' (and corresponding enhanced discriminatory ability). Similarly, we might expect predators to be highly discriminatory in their selection of prey according to the way they move and this has been observed (Mills, 1990).

■ Implications for wildlife practitioners

There are two levels at which the study of state may prove helpful for wildlife practitioners, managers and policy makers. One revolves around the definition of the state of a select number of specifically equipped wild animals being subject to known changing conditions, or proposed changing conditions, such as the construction of oil pipelines in Alaska or new roads in Tanzania (Dobson et al., 2010). Here, accelerometers may provide a seamless record of how animals exposed to the possible stressor react, both behaviorally and in a state sense. The manifestation of the stressor may not elicit an apparent change in behavior but may, nonetheless, be stressful, increasing stress hormone levels with all the detrimental effects that these incur (e.g. Kiank, Taché, & Larauche, 2010). The second value of the approach is more expansive. Larger numbers of animals within the environment equipped with accelerometers for general monitoring, or as part of a project primarily considering other aspects, should be able to provide enough information to examine a suite of important environmental issues ranging from how fat the animals are (because well-fed animals move differently to thin ones (Wilson et al., 2006)) through documentation of stress to animal health. Comparison of states of animals from different areas within the environment could not only help us compare the area- and site-dependent wellbeing of animals *per se,* but it could also help elucidate the dynamics of disease spread, a notoriously tricky element in modelling best strategies for managers (Gilbert et al., 2010). Indeed, given that state is considered one of the fundamental drivers of animal movement (Nathan, et al., 2008), we might expect that the definition of state coupled with examination of how this ties in with observed movement patterns to give us a hitherto unrealized ability to understand the dynamics of disease spread.

The worst case scenario is that the examination of micro-movement allows little practical definition of the specifics of animal state. This would be disappointing, and seems unlikely given the complexity and variety of accelerometry signals, but even this should still allow us to compare the norm with the aberrant so that practitioners could be alerted to unwanted changes in ecosystems that could be prevented if examination of the causes and treatments are undertaken in time.

We conclude from this preliminary study that animal-attached accelerometers show real potential for helping discern state in both wild and domestic animals. There are obvious caveats to our study which will require considerable work before the genuine value of the approach can be verified. Not least of these is the point at which a micro-movement becomes a behavior, although the ability of the accelerometers to distinguish between these is an academic, rather than a pragmatic, matter. Despite this, the diagnosis of subclinical illnesses such as, for example, bovine spongiform encephalopathy, which is notoriously difficult to diagnose (Atarashi et al., 2011), or a suite of other wildlife diseases, could prove a boon for wildlife practitioners.

■ Acknowledgements

The analysis of much of this work was made possible by the Royal Society/Wolfson visualisation lab at Swansea University. We thank Sharon Ahmadi & Angela Samuels for help collecting the data. Dr Luke Downey is supported by a National Health and Medical Research Council(NH&MRC) biomedical fellowship(APP1054279).

■ References

Atarashi, R., Satoh, K., Sano, K., Fuse, T., Yamaguchi, N., Ishibashi, D., et al. (2011). Ultrasensitive human prion detection in cerebrospinal fluid by real-time quaking-induced conversion. *Nature medicine, 17*(2), 175-178.

Butt, T., Ibrahim, L., Ball, B., & Clark, S. (1994). Pathogenicity of the entomogenous fungi Metarhizium anisopliae and Beauveria bassiana against crucifer pests and the honey bee. *Biocontrol Science and Technology, 4*(2), 207-214.

Clark, J. D., Rager, D. R., & Calpin, J. P. (1997). Animal well-being III. An overview of assessment. *Comparative Medicine, 47*(6), 580-585.

Darwin, C. (1998). *The expression of the emotions in man and animals*: Oxford University Press.

Dobson, A. P., Borner, M., Sinclair, A. R., Hudson, P. J., Anderson, T. M., Bigurube, G., et al. (2010). Road will ruin Serengeti. *Nature, 467*(7313), 272-273.

Duncan, I., & Petherick, J. C. (1991). The implications of cognitive processes for animal welfare. *Journal of Animal Science, 69*(12), 5017-5022.

Flavel, S. C., Koch, J. D., White, J. M., & Todd, G. (2012). Illicit Stimulant Use in Humans Is Associated with a Long-Term Increase in Tremor. *PLoS ONE, 7*(12), e52025.

Gilbert, M., Newman, S. H., Takekawa, J. Y., Loth, L., Biradar, C., Prosser, D. J., et al. (2010). Flying over an infected landscape: distribution of highly pathogenic avian influenza H5N1 risk in South Asia and satellite tracking of wild waterfowl. *Ecohealth, 7*(4), 448-458.

Grundy, E., Jones, M. W., Laramee, R. S., Wilson, R. P., & Shepard, E. L. (2009). *Visualisation of sensor data from animal movement.* Paper presented at the Computer Graphics Forum.

Halsey, L. G., Portugal, S. J., Smith, J., Murn, C. P., & Wilson, R. P. (2009). Recording raptor behavior on the wing via accelerometry. *Journal of Field Ornithology, 80*(2), 171-177.

Hebblewhite, M., & Haydon, D. T. (2010). Distinguishing technology from biology: a critical review of the use of GPS telemetry data in ecology. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1550), 2303-2312.

Hoy, C. W., Head, G. P., & Hall, F. R. (1998). Spatial heterogeneity and insect adaptation to toxins. *Annual Review of Entomology, 43*(1), 571-594.

Kiank, C., Taché, Y., & Larauche, M. (2010). Stress-related modulation of inflammation in experimental models of bowel disease and post-infectious irritable bowel syndrome: role of corticotropin-releasing factor receptors. *Brain, behavior, and immunity, 24*(1), 41-48.

Lazarus, R. S., & Folkman, S. (1984). Stress. *Appraisal and Coping, New York.*

Lima, S. L., & Zollner, P. A. (1996). Anti-predatory vigilance and the limits to collective detection: visual and spatial separation between foragers. *Behavioral Ecology and Sociobiology, 38*(5), 355-363.

Lundberg, U. (2005). Stress hormones in health and illness: the roles of work and gender. *Psychoneuroendocrinology, 30*(10), 1017-1021.
Mendl, M., Paul, E. S., & Chittka, L. (2011). Animal behaviour: Emotion in invertebrates? *Current Biology, 21*(12), R463-R465.
Mills, M. (1990). Kalahari Hyaenas: The Comparative Behavioural Ecology of Two Species, 1990: Unwin Hyman, London.
Nathan, R., Getz, W. M., Revilla, E., Holyoak, M., Kadmon, R., Saltz, D., et al. (2008). A movement ecology paradigm for unifying organismal movement research. *Proceedings of the National Academy of Sciences, 105*(49), 19052-19059.
Parrott, A. C. (2013). Human psychobiology of MDMA or 'Ecstasy': an overview of 25 years of empirical research. *Human Psychopharmacology: Clinical and Experimental, 28*(4), 289-307.
Saarenmaa, H., Stone, N., Folse, L., Packard, J., Grant, W., Makela, M., et al. (1988). An artificial intelligence modelling approach to simulating animal/habitat interactions. *Ecological Modelling, 44*(1), 125-141.
Sekiya, N., Nagasaki, H., Ito, H., & Furuna, T. (1997). Optimal walking in terms of variability in step length. *Journal of Orthopaedic & Sports Physical Therapy, 26*(5), 266-272.
Shepard, E. L., Wilson, R. P., Quintana, F., Laich, A. G., Liebsch, N., Albareda, D. A., et al. (2008). Identification of animal movement patterns using tri-axial accelerometry. *Endangered Species Research, 10*(47-60), 2.1.
Thayer, J. F., Yamamoto, S. S., & Brosschot, J. F. (2010). The relationship of autonomic imbalance, heart rate variability and cardiovascular disease risk factors. *International journal of cardiology, 141*(2), 122-131.
Watanabe, S., Izawa, M., Kato, A., Ropert-Coudert, Y., & Naito, Y. (2005). A new technique for monitoring the detailed behaviour of terrestrial animals: a case study with the domestic cat. *Applied Animal Behaviour Science, 94*(1), 117-131.
Wilcox, J. A., & Wilcox, A. H. (2009). Movement disorders and MDMA abuse. *Journal of psychoactive drugs, 41*(2), 203-204.
Wilson, R. P., Scolaro, A., Quintana, F., Siebert, U., Thor Straten, M., Mills, K., et al. (2004). To the bottom of the heart: cloacal movement as an index of cardiac frequency, respiration and digestive evacuation in penguins. *Marine Biology, 144*(4), 813-827.
Wilson, R. P., Shepard, E., & Liebsch, N. (2008). Prying into the intimate details of animal lives: use of a daily diary on animals. *Endangered Species Research, 4*(1-2), 123-137.
Wilson, R. P., White, C. R., Quintana, F., Halsey, L. G., Liebsch, N., Martin, G. R., et al. (2006). Moving towards acceleration for estimates of activity-specific metabolic rate in free-living animals: the case of the cormorant. *Journal of Animal Ecology, 75*(5), 1081-1090.
Yang, C.-C., & Hsu, Y.-L. (2010). A review of accelerometry-based wearable motion detectors for physical activity monitoring. *Sensors, 10*(8), 7772-7788.