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Current Opinion in Neurobiology - Sensory systems
Editorial overview
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All creatures, great and small, are connected by mere threads to their sensory surfaces. The primary living of the fruit fly (*Drosophila*) depends on information from a few hundred olfactory nerve fibres. The finch (*Taeniopygia*) has only about 5000 fibres per ear to provide the information it needs to parse and memorise the complex of time, tone and harmonics of the song emitted by its father. *Drosophila* also sings – a 'love' song – but his prospective mate has information from only a few hundred auditory fibres to judge whether his performance has enough of the 'Y-factor' to be the father of her offspring. Even fewer fibres lead from the sense organs that provide the information allowing a curious *Rattus* to judge the texture of a surface using a single whisker, or for a blind person to read Braille. A few thousands of fibres are needed to keep vertebrates balanced against the pull of gravity, and the number is even fewer for the organs of balance and proprioception in invertebrates.

Although the richness of our own sensory perceptions hangs by these threads, the effortlessness with which we listen to each other (or Mozart), navigate around a city (or our lab.), or simply kick a football around the park, makes these tenuous connections of our brain with our sense organs invisible. More than that, all our decisions are based on these sparse messages and the memories they create. Why on earth did evolution ever come up with a design for sensory pathways that gives us such minimal data about our environment? How is it that animals both great and small extract such exceptional behavioural competence from this limited sensory input? Clearly there is something extraordinary happening in the central processing circuits, thus our choice of experts reflects our own curiosity about these questions.

The questions addressed by our authors are specific instantiations within a conceptual framework of neurobiology that even Darwin would have recognised. While comprehensive answers to these questions of why and how are still a long way off, the reviews collected here reveal the relentless search for principles of operation across a range of sensory 'platforms' in vertebrate and invertebrate species. Of course, Theodosius Dhobzansky's view that 'nothing in biology makes sense except in the light of evolution' [1], means that none of us should be surprised, given evolutionary mechanisms have been hard at work for many millions of years, to find that some principles and their implementations are common for a given function, and some are not. Thus, the olfactory organs of *Drosophila* and *Mus* have interestingly close parallels, while the cochlear of *Mus* and the antennal hearing organs of *Drosophila* have in common mechanosensory transduction, but not a lot else. Different strategies of processing are also in evidence, so whereas the mechanical features of *Drosophila*'s antennal organs seem tuned

2 Sensory Systems

for detecting low frequency love songs, where the beat is more significant than the melody, the peripheral machinery in *Mus* and *Taeniopygia* transmits a wide range of frequencies centrally so that the discrimination of calls of low or high behavioural significance occurs beyond even the primary auditory centres. However, more seems to be conserved than not across sensory systems, even if it is true, as Francis Crick pithily claimed, 'God is a hacker.'

A large segment of sensory physiology is concerned with causation, where the question is about which stimuli elicit a given response. This question is identical to the first of Nico Tinbergen's four questions [2], which he devised for his field of neuroethology, but it applies equally well to sensory physiology. (His other three questions, also about mechanism, concerned ontogeny, phylogeny and adaptation, which also apply well to issues reviewed here, like coding, learning, and choice.) The measurements and the associated theoretical interpretations of this relationship between stimulus and response have been made on different scales, from molecular to cellular, from circuits to behaviour. It is increasingly common for these multiscale investigations to be made in the same animal and so bind together cause and effect more directly. This inevitably brings us to another central question: how do animals combine their multiple sources of sensory information to create a coherent and unified sense of being an individual – a 'self' – in a contingent world where causal links need to be learned so that events can be predicted and the appropriate behaviour can be selected? As many of the reviews here indicate, the successes of multiscale and multimodal approaches have encouraged us to be more technically ambitious and also to push the development of more sophisticated theoretical approaches.

Technically we have never had it so good. In addition to the gold standards of physiological recordings at single neuron resolution and the ability to visualise structures at subsynaptic resolution, these reviews show that we can take advantage of the greatly expanded reach of the optical microscope to study single neurons or populations of neurons *in vivo*. While the low spatial and temporal resolution of methods like EEG and structural and functional magnetic resonance imaging are still a barrier to investigations of neural processing and circuits in humans, these 'non-invasive' techniques have certainly narrowed the gap between humans and the much finer resolution methods that require invasive work in other primates. This gap between human and animal studies also has also been narrowed by the development of computational approaches that span multiple scales and are species-independent. These computational approaches are an essential component of our reviews, for through them we can explore general principles of neural processing. However, it is far from settled as to what should appear on the core list of general principles. Even the issue of representation of sensory information,

so fundamental to computation, still stirs a pot filled with debates of cardinal neurons versus distributed ensembles, rate coding versus temporal coding and *tabula rasa* versus specific circuits. For this reason, a number of different approaches to central problems of neural computation and a number of different sides of controversies are represented here (amicably, of course).

Computational theories of neural processing traditionally divide into two streams, the probabilistic and the deterministic. Both have their roots in mid-20th century developments, most famously in the deterministic model of the action potential by Alan Hodgkin and Andrew Huxley (still the acme of computational models) and by probabilistic models, such as that for synaptic transmission by Hodgkin's erstwhile collaborator, Bernard Katz. Both these streams continue to be fruitful, even in the more complex theoretical environment of neural circuit models. However, one of the central problems that any nervous system has of computing on inherently noisy components was pointed out by a Presbyterian cleric in the 18th century: 'Now that the errors arising from the imperfection of the instruments & the organs of sense shou'd be reduced to nothing or next to nothing only by multiplying the number of observations seems to me extremely incredible.' [3]. Bayes' world is stochastic and so is ours. For example, thermal noise is the reason we can detect single photons, but not single phonons. However, there are many sources of noise other than thermal noise in the nervous system. John von Neumann knew how to limit the noise due to the numerical procedures in his design of digital computers, but was baffled as to how this was achieved by biology: 'The nervous system is a computing machine which manages to do its exceedingly complicated work on a rather low level of precision: [according to the above,] only precision levels of '2 to 3' decimals are possible. This fact must be emphasized again and again because no known computing machine can operate reliably and significantly on such a low precision level.' [4]. In the light of this quandary, the use of probabilistic models, such as those based on Bayes' Theorem, is an inevitable and pragmatic step in developing descriptive and predictive models of the operation of nervous systems.

Because of Moore's Law [5], the 21st century now sees ambitious attempts to simulate the brain on digital computers. Although presented as the path to generating a brain '*in silico*', these simulations take place in John von Neumann's hardware, which too easily permits the unwary to neglect many of the constraints of physics that animals experience. The discretisation of time, and of integer variables, inevitably has a cost in simulations of biological neurons, which generate continuous analogue values and asynchronous events. Also, living as they do by the benevolent hand of the power grid, and not by their own wits, supercomputers do not face the challenges that

we animals do in having to survive in the real world. Their world has to be encoded in the machine, and so is inevitably impoverished. One serious consequence of this simulated environment is that most theorists have yet to give speed the weight it deserves. However, there is an alternative: one group of engineers has grasped the nettle and builds 'neuromorphic' devices, based on hybrid analogue–digital electronics. When pressed to explain why they do not follow the traditional simulation route using digital computers, the more philosophical of them refer to Giambattista Vico's principle of 'verum factum': 'The criterion and rule of truth is to have made it.' [6]. Emulation, rather than simulation, is their reason for developing a true '*in silico*' approach. Silicon neurons, being actual physical objects, not virtual electronic objects in a digital computer, are subject to the same constraints of physics as biological neurons. Thus noise and time are real, computations are asynchronous and local, the neurons are analogue devices and transmit by spikes. These are hallmarks of silicon neurons and circuits, just like their biological counterparts. We thus could not forebear to commission a review on this new

toehold in our ascent of the mountain of ignorance about the brain.

Our authors have independently and collectively done a great job in reminding us of three salient facts: we are up against a hard problem, we are making impressive progress and – evolution is our friend.

References

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