

Guest Editorial

Applied neuroscience

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This issue presents several reviews, primers and essays on applied neuroscience covering everything from computer vision and pain to the law. Neuroscience is often driven by pure curiosity: How does the brain work? How does such complexity evolve? Is there an underlying code that is the equivalent of DNA for the mind? There are certainly mysteries galore. But unlike other curiosity-driven areas like cosmology or astrophysics, neuroscience is rich in applications. Like genetics and biology, it has the potential, some of which is now being realized, to provide not just answers, but cures, for pathologies and traumas, and applications of new brain-computer interfaces. Neural prosthetics of all kinds, for hearing, sight, lost or paralyzed limbs, and the brain-machine interfaces that make them run are becoming more and more commonplace. Certainly, cochlear implants have become the poster child of applied neuroscience, soon to reach 500,000 people who now have some form of hearing. Vision implants are progressing, although much more slowly. Deep brain stimulation to help Parkinson's and depression, among other conditions, is now a growing success story. Recovery of motor control for paralyzed limbs has begun as the field of brain-controlled prosthetics takes off. And a better understanding of the neural basis of choice provides a more solid grounding for legal issues of ethics and morality.

These are good days for real applications of neuroscience that will make deep and meaningful contributions to society. And yet, neuroscience is still a small player in science funding. Although individual projects in other disciplines receive massive funding, like the Large Hadron Collider at \$9Bn, the ITER fusion reactor, \$7Bn, the Cassini-Huygens satellite \$3.3Bn, and development for just one drug, Lipitor, \$4Bn, last year all of US neuroscience received only \$5.5Bn, about 15% of the NIH budget, divided among 16,000 projects. The US

BRAIN Initiative at \$4.5Bn over 12 years and the now controversial European Human Brain Project at \$1.6Bn over 10 years are encouraging, though dwarfed by the \$100bn it took to land on the moon. For the moment, there is nowhere near this level of funding to, how should we say it, land science on the cortex.

Beyond this central core of burgeoning applications, like deep brain stimulation, cochlear implants, and brain-controlled prosthetics, lies a great number of growing and even eclectic new directions. Many of these involve applying neuroscience to artificial intelligence. Long ago it was the fashion to make computers solve problems as humans might, attempting to transfer expertise in vision, language, and chess, among other areas, into working code. "Computers will defeat the top grand master in chess in 10 years," said Herb Simon in 1957. In fact, it took 40 years, and not by using any methods that resembled human expertise. Artificial intelligence approaches to language and vision also abandoned any pretense to mimic biological processes and migrated to brute-force data techniques. But the pendulum has now begun to swing back and biology-inspired approaches are being reconsidered, whether with deep learning or voice interpretation in severe noise or biomimetic and "attentive" robots. Even further afield, applications of neurosciences stretch in many unexpected directions. These innovations can be as unbounded and unpredictable as the basic research that inspires them. Some of these eclectic directions are seen in this issue, with the coverage of applications of neuroscience to law, economics, and social sciences.

This review of applications should be a truly encouraging sign that neuroscience is meeting its goals in providing new ways to overcome pathologies, improve quality of life, and extend neuroscience into new areas of applications. New neuroscience projects that are vast in diversity and massive in scale are bringing promising applications, together with the science behind them, to the next level.

In their review, Richard Andersen and coauthors describe how to derive the intent of the subject by tapping into cortical areas upstream of the motor cortex. This new approach will add to the range of interfaces available for current work on the control of

paralyzed limbs and prosthetic artificial limbs, using implanted stimulators that augment residual signals in damaged spinal cord. These new techniques for direct brain control show great promise, but are just beginning, having reached nowhere near the wide application of cochlear implants.

Simon Little and Peter Brown cover three truly encouraging advances made in previously intractable neurological disorders, driven by primary neuroscience. Pharmacogenetics genetically provides replacement for lost dopamine; adaptive deep brain stimulation can now be controlled by neural signals and finally, optogenetics provides the opportunity to repair large-scale, network-level dysfunctions. Deep brain stimulation follows cochlear implants as a remarkable achievement of neuroscience, with about 100,000 implants worldwide for treatment of Parkinson's as well as headache, Tourette's, epilepsy, and now psychiatric disorders like depression, and anxiety.

Frank Sengpiel reviews the evidence for neural plasticity and argues that indeed the brain can regenerate. Recent animal studies suggest that visual cortex plasticity in particular can be restored or enhanced later in life by removing the molecular brakes that normally limit plasticity to early critical period.

Dario Floreano and coauthors give an overview of the work at the intersection of robotics and neuroscience and highlight the most promising approaches and areas where interactions between the two fields have generated significant new developments for both fields. They argue that the physical behavior and embodiment inherent in robotics generate valuable insight into the function of nervous systems, and that, in return, neurally inspired algorithms and devices are able to give robots life-like capabilities.

Cox and Dean take a look a neuroscience-inspired computer vision starting from early models of McCulloch and Pitts and Rosenblatt, through the connectionist era and its subsequent abandonment, to the deep-learning models of the present day. Following the early connectionist boom of the 1980s, neural models were supplanted by engineered solutions to particular computer vision problems that avoided any biological strategies. This long "A.I. Winter" was relieved by



Thought control of robotic limbs.

By imagining the movement of her own arms, a paralysed woman controls a robotic arm to serve herself some coffee, the first time in 15 years that she has been able to do so. An array of 96 electrodes implanted in her motor cortex records signals for the imagined limb movement and these are then converted into commands to the robotic arm. Credit: braingate2.org

the arrival of deep-learning techniques with multiple layers mimicking the many-layered structure of the visual cortex. The success of these new techniques can be seen from the enormous investment of industry giants such as Google, Facebook, and Baidu. Over a short period of time, neural network models went from an obscure relic of the past to a dominant force in nearly every field of machine learning and perception. Cox and Dean review several aspects of biological neural computing that may be incorporated in the new models. Feedback is becoming important but, in contrast, modeling neurons at the spiking level has yet to be shown to be useful. They suggest that models should move to analyzing dynamic images and incorporating interactions with working memory, reward, other senses. According to Cox and Dean, we are seeing the start of a new era when the fields of neuroscience, computer vision, and machine learning have more to say to one another than ever before.

In their primer, Essi Viding and coauthors describe how neuroimaging approaches are providing insights into psychopathy, a personality disorder that harms both the affected individual and society in general. They point out that the challenge for the field is to translate the new research into

new intervention techniques and that research in some areas such as empathy induction and punishment has shown limited success for treating psychopathy.

In a complementary Primer, Singer and Klimecki describe recent findings on empathy and compassion, the traits that seem to be defective in psychopaths, from social and affective neuroscience. Neuroimaging has suggested, for example, that empathizing with another person's feelings relies on the activation of neural networks that also support the first-person experience of these feelings. Further research focuses on socio-affective training techniques to affect functional brain plasticity, brain structure, and a wide range of health and behavior-related variables.

In a mini review, Zhang and Seymour present an overview of pain treatment. Why does pain have to hurt so much? New technologies for chronic pain management also offer prospects for the measuring and diagnosing pain. They also describe how new optogenetic techniques have the potential to transform pain control.

Colin Camerer's Primer explains how the neural basis of economics is progressing rapidly, helped along by the fact that mathematical expressions of neural computation can be

compared to the mathematics used to describe economic-utility maximization. He also describes the efforts to combine data from many studies with socioeconomic outcomes and genome-wide association data to greatly improve the statistical power available to identify associations.

Machery and Carlyon explain the essentials of cochlear implants, the first example of a neural prosthesis that can substitute for a sensory organ. These have become a standard clinical procedure for congenitally deaf children. Many cochlear implant listeners can use the telephone and follow auditory-only conversations in quiet environments. They describe how sounds are degraded as a result of both device and sensory limitations, and discuss current research trends aiming to improve speech perception, particularly in challenging listening conditions.

Finally, in one of three wide-ranging essays, Vincent Walsh tackles a new approach to neuroscience through sport. He points out that elite athletes provide an unrecognized opportunity to explore neural activity at its top level in natural settings. Consider the precision and pace of response when Rafael Nadal faced Novak Djokovic in the Wimbledon final in June: their performance required extraordinarily rapid visual processing, strategic and motor planning, as well as action. Walsh emphasizes that current laboratory approaches cannot or have not yet investigated the levels of processing speed, bandwidth, and intermodule coordination seen in sport. The neuroscience of sport is not just the study of remarkable individuals with differently constructed, freakishly fast nervous systems. Instead, elite performance identifies the processing architectures necessary for real, complex behavior and this applies to all of our nervous systems even if with less elegant outcomes and lower prize winnings.

In his essay, John Tsotsos considers the various degrees of overlap between biological and computer vision. He points out that biology is capable of fast, general vision, and skilled performance, both requiring computational complexity that would overwhelm any current artificial technologies. Tsotsos reviews the strategies from neuroscience that are being transferred to artificial systems in an attempt to get them up to our

speed in complex tasks. For example, one important constraint to reduce complexity is attention, the selection of a subset of the input data or a subset of potential outputs that focus on the most relevant options. Strategies are now being developed to operationalize 'attention' and other biologically based approaches, and transport them to intelligent devices.

And in a third essay, Buckholtz and Faigman bring in the law. After all, once the new brain-machine interfaces are in place, who is to blame when your prosthetic arm kills someone? These instances where we might look to the technology to find responsibility for our actions shade into cases where our better understanding of the neuroscience of behavior suggests neural sources for antisocial acts. We can blame murder on Ambien or Twinkies, on YYX chromosomes or on just being male. Where does responsibility fall, morally and legally, once we have more comprehensive explanations of violent behavior from neuroscience. How reliable is the use of neuroscience as evidence in court. Buckholtz and Faigman consider the difficulty of evaluating scientists' testimony as well as the use of fMRI or other biomarkers of lying, and the use of predictive constraints on individuals with neural correlates of antisocial behavior. Neuroscience, perhaps more than any other science, will become increasingly involved in deciding legal cases and policy. Buckholtz and Faigman offer some guidance to the issues that will be raised as this progresses.

In reading through these reviews, primers, and essays, it is clear that neuroscience is now a major player in medicine and the development of new learning and legal methods. At one time, a 'moon shot' meant that your project was ambitious but had almost no chance of succeeding. But, of course, we did land on the moon, and neuroscience has now reached a level of maturity and progress where a 'moon shot' for neuroscience, should mean just that, a massive moon-landing level of investment to bring the fruits of neuroscience, many on display in this special issue to society.