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EDITORIAL

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Neuroengineering—a renaissance in brain science: Tutorial Series from the 3rd Neuro-IT and Neuroengineering Summer School

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Within a stones throw of the celebrated Rialto Bridge, students and faculty gathered together at the height of summer over six long days to focus their minds on a new emerging discipline—*neuroengineering*. The searing temperatures of Venice and lack of air conditioning required stamina and strong motivation towards the subject. So what is neuroengineering, what makes it so interesting and what brought these individuals together?

One definition we can adopt is that neuroengineering embodies a pragmatic, engineering methodology to *understanding*, *representing*, *manipulating* and *augmenting* the nervous system. It advocates understanding the brain through building physical implementations, sparing prejudgment on the conceptual basis or substrate of that implementation. In one sense we may view this as a very new activity, since it has undoubted close relationships to recent developments in neuroprosthetics and silicon sensory system implementation, for instance. Yet in its conceptual basis and motivation we can trace back a long history with deep intellectual roots.

In what he called the *new science*, the Italian philosopher and social theorist Giambattista Vico summarized his approach as *verum et factum convertuntur*, that 'the true and the made are ... convertible' [1]. Vico's vision of science, unlike that of his contemporary Rene Descartes, was as a 'genus or mode by which a thing is made'. Yet, any cursory examination of modern science demonstrates that we have largely been left, instead, with the legacy of Descartes, who envisioned an explanatory natural science, defined purely in terms of a reduction to known principles and facts, through a purely deductive process [2]. The reductionism Descartes advocated has been highly productive in modern science in terms of detailing an incredible diversity of physical and natural mechanisms—somewhat reminiscent of the Victorian fashion for collecting and cataloguing. Yet reductionism, *in itself*, says nothing about how these mechanisms should be fitted together to generate *function*. Describing the brain as a zoo of lower level components and mechanisms (ion channels, synaptic function, neurotransmitter release, membrane properties and so on) does not guarantee an understanding of the system's behaviour or interrelationships between these components and the phenomenal world. In terms of the development of a modern cognitive science this last piece seems crucial.

We see that Vico's plan for science is just as valid today for understanding the brain, perhaps more so, as we face an ever growing mountain of largely isolated empirical observations of the brain which desperately require synthesis and interpretation. Neuroengineering seeks to meet this challenge by building physical implementations, constrained by these empirical data, explicitly testing, quantifying and measuring their relationship to brain function by placing them firmly within a systems and operational context. The neuroengineer alongside his/her namesake, the neuromorphic engineer, explicitly addresses the question: *do we understand the brain sufficiently well to build and manipulate it?* By building such physical models or augmenting and manipulating the nervous system we explicitly test our understanding, in particular the implicit assumptions that biologists may make in terms of systems function, system constraints and system component interaction from observing the behaviour of the components. In some sense, this represents the ultimate testing crucible for a brain theory.

A successful outcome for the neuroengineer is to produce an embodied physical implementation that incorporates a known set of biological mechanisms, which when acting together are demonstrated to function equivalently to the target brain centre when observed within the context of the world. Nothing precludes us from incorporating real biological components in these built systems to form hybrid architectures which can be tested in the same way. Thus, physical implementations are a crucial tool for the neuroengineer, since they can subsequently be tested in the world, under similar constraints and operating conditions to those faced by the nervous system (note that this is very different from bio-inspiration which does not generally seek an explanatory role for the models that are built). This is also distinct from other integrative brain sciences, such as computational neuroscience and neuroinformatics in which physical implementations do not typically feature.

By reducing the potentially infinite set of possible biological mechanisms at different levels of organization down to a limited and sufficient subset, which when combined demonstrate equivalent functional behaviour, the neuroengineer demonstrates function that satisfies equivalent performance measures. In a subsequent iterative process, these mechanistic models of brain function show that neuroengineering models can be further reduced by extracting the underlying principles which make them function effectively. Typical measures for comparison include, but are not limited to, psychophysical performance and behavioural quantification. In order to be faithful to the approach, the methods used to measure the performance and function of these models must not discriminate between the biological system and its counterpart physical artifact on account of the function being measured—they should be interchangeable in the sense of this function-limited Turing test.

It was this approach that was represented at the Venice Summer School this year, which brought together 70 faculty and students in an unusual series of lectures covering both neuroscience and its physical implementation with the theme of ‘Neuroengineering of Cognitive Function’. The Summer School began in 2003 in honour of the late Massimo Grattarola, with the philosophy of fostering this unique interdisciplinary community at the European level. Grattarola was a pioneer of interfacing neural systems to computers, whose work on this dating back to the early 1990s laid the foundations for many of the topics considered in *Journal of Neural Engineering* today [3, 4]. His vision and contribution to the subject will be missed and the School provides a fitting tribute to his contribution.

Two approaches to modern neuroengineering were represented amongst the lectures of the Summer School. In a reverse engineering mode, we witnessed modelling and the application of data analysis tools to the nervous system in an attempt to uncover its design principles. This process of extracting principles and processing mechanisms salient to cognition from biological data was emphasized strongly. In particular, Wilson described how REM sleep participates in memory formation in the hippocampus, Engel, Fries and Orban on how the principles of dynamics and synchrony underpin visual processing, Gallesse and Sanguineti on multimodal integration during internal sensorimotor processing, Büchel on emotional processing and Markram on emergent properties of cortical microcolumn architectures.

We also saw how these underlying principles and mechanistic details are effectively then evaluated in a forward engineering mode, with an emphasis on physical implementations tested in the world. This was a key topic of many of the lectures presented at the Summer School. Schmidhuber, for instance, emphasized how neural models can effectively solve real-world control tasks, König demonstrated how unsupervised learning of neural models evolves receptive field properties analogous to that seen in the visual system during exposure to natural stimuli, Pearce focused upon neural coding related to natural plume navigation in an artificial moth, Sandini on the evolution of neural models in embodied artifacts through real-world interaction, Araújo on optic flow computation and its relationship to machine vision, Ijspeert on central pattern generator modelling and its application to robotics, the relationship of neurodynamics to locomotion by Passeman, and Verschure emphasized the reciprocal relationship between neural systems and the environment.

Such forward engineering approaches can also be used to manipulate or augment the nervous system and its input/output relationships with the world, for instance by building invasive or non-invasive neuroprosthetics, or brain–computer interfaces. In this case our understanding of brain function can be explicitly tested by assessing the function or performance of a hybrid neural system. This approach brings to bear many areas of engineering, including signal processing, tissue engineering, biomaterials and robotics. Inherent in this approach is applying our understanding found in the first approach and all of neuroscience and testing these assumptions through direct manipulation of the nervous system and/or how it interacts with the world. Critically, this last component again provides a test of our understanding in a practical scenario with quantitative outcomes. Examples at the Summer School included lectures by Kral who considered the relationship between natural and electrical stimulation in a cochlea implant, Fernandez, who considered the clinical and experimental aspects of a cortical visual neuroprosthesis for the blind (Fernandez *et al*, this issue, p R1), Müller and Wolpaw who discussed aspects of signal processing and machine learning applied to brain–computer interfaces, Erlhagen who has applied dynamical field models to robotics, König who experimented with augmentation of the senses through wearable technology (Nagel *et al*, this issue, p R13) and Goebel who demonstrated learning to play BOLD brain pong with fMRI neurofeedback.

When combined, these forward and reverse neuroengineering approaches permit an evaluation phase that is missing in much of current brain theory. The process often generates additional hypotheses and predictions that can be explicitly tested in biology. Hence we see that neuroengineering is a complex dyadic interactive activity between the physical and life sciences, from which both stand to benefit. This complex relationship between model building, evaluation and its relationship to empirical life science was discussed by Webb.

Successful neuroengineering not only acts as an existence proof of our understanding of specific brain centres and subsystems, but also produces a tangible technological outcome with well specified performance criteria. This technological outcome of the neuroengineering approach is highly relevant in our search for more flexible and adaptive information technologies. We follow the solutions that the brain adopts to information processing not because they are necessarily optimal but that billions of years of evolution has generated efficient and robust sensorimotor information processing solutions adapted to the physical laws of the world around us. It is for this reason that the EU Framework Programmes became strongly motivated to invest significant funding for such interdisciplinary research (70 million Euros in total over the past 5 years) under its Future and Emerging Technologies Programme by launching two Proactive Initiatives, 'Neuroinformatics for Living Artefacts' and 'Life-like Perception Systems', in 2002 which came under the umbrella of the Neuro-IT network (www.neuro-IT.net), which specifically considers these technological outcomes at the European level. From its outset the Summer School involved members from the newly formed Thematic Network, Neuro-IT which is uniquely placed at the intersection of neuroscience and information technology at the European level and provides a natural partner in this symbiotic relationship between brain understanding and emerging technology.

This Tutorial Series provides a permanent record of the intellectual investment made by the Faculty in addition to the streaming of lectures which we have made freely available at www.neurolectures.org. The Faculty were encouraged to write original tutorials that summarize the state-of-the-art in some aspect of neuroengineering. Many chose to do so and we are delighted to present this series. As a collection we hope it will it will reflect the diversity of this interesting topic.

We expect that this area of research can look forward to a bright future, as we witness an inexorable convergence of thinking between the life sciences, physical sciences and technology. The subject area is already the focus of new research and teaching programmes in neuroengineering represented at Harvard, MIT and UCLA as well as new dedicated conferences by the IEEE and newly launched journals such as *Journal of Neural Engineering* and *Journal of Neuroengineering and Rehabilitation*. The Summer School was a great success in identifying these points of contact between technology and neuroscience, and we expect it will have a long and productive future, stimulating interactions between faculty and students that are so critical to its growth. There could be no more appropriate setting for a Summer School on neuroengineering than Italy, which from an historical perspective is in some sense its natural home.

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