Guest Editorial: Special Issue on Cognitive Science

Why should a special issue of the IETE Journal of Research be devoted to Cognitive Science? Because there is a revolution taking place in our understanding of the brain and its product, the mind. Cognitive Science is the study of the mind, and understanding the rules by which the brain and mind work will have enormous consequences not only for understanding the human brain but also for making machines of the future that compute or process information. Cognitive Science, together with Neuroscience, is the next great frontier in the history of science, and scientific knowledge is the driver of technology.

The human brain is the most complex machine in the universe. It has 100 billion (10**11) cells or neurons, and each neuron interconnects with hundreds of other neurons via, on average, 10 thousand (10**4) connections or synapses. Thus, the brain has 10**15 synapses - this staggering number of connections is one reason for the complexity of brain processing. Another is the precision of wiring between neurons in order to make networks and modules. Neurons are not simply interconnected with any and all other neurons; rather, they make precise connections with a subset of cells and form networks that process information. Networks are the engine of the brain, for they transform simple inputs to make complex outputs, often via nonlinear operations. Complexity and nonlinearity are the essence of brain function, and of the mind.

Cognitive science aims to understand the rules of the mind. Till recently, the study of the mind was considered to be the realm of philosophy alone. Under the sway of behaviorism, the mind was not even considered an important subject of study: all operations of the mind were considered to arise from a black box that learnt to produce an output when conditioned by reward. However, the rise of cognitive science has transformed this view. We now know that the mind has specific domains of operation, such as language, vision and memory. While these domains partially overlap, they also arise from specific brain modules that are themselves created by a combination of genes and environmental influences. And perhaps most importantly, the brain and mind can be considered to process information and carry out computations – that is, logical operations on inputs in order to produce outputs that exemplify our human capacities. Thus, almost every sentence we utter is new and unique in some way – we have in our brains the capacity to string together words in ways that make sense, and we can do so in an infinite variety of ways. Even something as automatic as vision involves recognition of patterns and objects in scenes that we have almost never encountered before in exactly the same way – yet we see effortlessly. All this is possible because we have in our brains not the details of every possible sentence or view, but the rules of how to construct sentences and views from simple elements. This is how the brain creates the mind.

The ideas and metaphors of Computer Science and Electrical Engineering have had a profound impact on Cognitive Science and Neuroscience; in turn, the more we understand how the brain wires itself and processes information, the more insights we will derive for constructing intelligent devices. This Special Issue brings together papers that span a wide range of topics in the brain and cognitive sciences. These include brain mechanisms of sensory perception, including vision and audition; mechanisms of learning and cognition; and principles of network optimization. The methods range from neurophysiological study of neurons in animals to computational models of neuronal networks to psychophysical studies in humans. The goal of the Special Issue is not to provide a comprehensive review but rather a glimpse of some ideas and approaches that constitute ongoing work in this young and dynamic field.

Several papers deal with vision and its mechanisms. Vision is a crucially important sensory system for humans and other primates. Nearly half of the human brain – and even more in monkeys – is devoted directly or indirectly to vision. Understanding visual perception and processing thus provides a crucial window into the operations of the brain and mind. The basis of vision is the selective responses of cells in the visual pathway of the brain to specific features of images. Orientation selectivity of neurons in primary visual cortex or V1, the first stage in the cortical processing of vision, underlies our ability to see shapes. Valentin Dragoi, Jitendra Sharma and Mriganka Sur describe recent work showing that V1 neurons construct and change their orientation-selective responses as they are stimulated visually (via bottom-up processes) or as task or behavioral conditions change (via top-down influences). Orientation plasticity can be induced rapidly, by adaptation on the time scale of visual fixation, or by an internal representation that governs where we look next. Such changes continuously influence vision. A plausible mechanism for dynamic changes in orientation selectivity is that feedback projections from higher areas modulate the strength of recurrent connections between local V1 neurons, and thus effectively modify the amplification of feedforward inputs to V1 neurons.

Basabi Bhaumik and Mona Mathur examine the basis of orientation selectivity of "simple" cells in V1. They present a feedforward model of the visual pathway consisting of the retina, the visual thalamus (or lateral geniculate nucleus, LGN) and primary visual cortex, and estimate the ability of the model to account for tuning in simple cells in layer 4 of the cortex. They show that the use of a spike threshold improves the tuning in a significant manner.

Rajesh Rao, Margaret Livingstone and Terrence Sejnowski propose a mechanism for the development of receptive fields of "complex" cells in visual cortex. They describe a computational model which suggests that the source of the non-linear receptive field properties of complex cells is the pattern of excitatory and inhibitory connectivity in recurrent cortical networks. This pattern of connectivity may emerge as a consequence of spike-timing dependent plasticity in cortical circuits specialized for motion detection. More generally, spike timing dependent plasticity appears to be a key mechanism responsible for the development of response properties of cells in a cortical network.

Besides electrophysiology and modeling, another approach to decipher the workings of the visual system is through psychophysical experiments. Pawan Sinha describes a set of ingenious experiments which demonstrate that the default visual recognition strategy in humans is overwhelmingly biased towards the use of two-dimensional projected shape, though it is possible for humans to use depth information when explicitly instructed to do so. Sinha convincingly argues that the visual system is rather opportunistic, capable of using whatever attributes of an object as necessary to accomplish a task.

Mandyam Srinivasan and Shaowu Zhang make a strong case that brain size is not necessarily a reliable predictor of perceptual capacity or cognitive abilities. Their work suggests that learning and perception exists as a continuum across the animal kingdom. Even honeybees, which possess a "simple" but specialized nervous system, learn the visual features of a pattern in an abstract sense, and use this knowledge to distinguish between other patterns that they have never previously encountered. They also exhibit top-down processing, and can form complex associations.

The control of eye movements involves a number of brain areas, and is a powerful system for studying how the brain selects and controls a movement. Aditya Murthy describes experiments on cortical activity associated with selecting a target for an eye movement, and on the neural processes that regulate the production of the movement. He demonstrates that activity associated with salient visual targets progressively dominates in cortical neurons, and leads to growth of movement-related activity towards a threshold for initiating an eye movement. Such a finding may represent a general principle by which the brain regulates voluntary movements.

Similar to the visual system, the auditory system also provides elegant examples of complex information processing. In the real world, several sound sources may simultaneously change their loudness, location, timbre, and pitch. Yet humans, like many other animals, are able to integrate effortlessly the multitude of cues arriving at their ears, and to derive coherent percepts and judgments about the different attributes of each source. Shihab Shamma examines how auditory information is encoded at several stages in the auditory pathway. A nonlinear compressive stage in cochlear hair cells converts signals into a pulse representation which retains information about zero-crossings. By the time signals reach the auditory cortex, multiscale analysis is possible, allowing the extraction of specific spectral and temporal features from the input.

Ramesh Rajan describes plasticity in the auditory cortex after selective damage to auditory receptors in the cochlea. High frequency hearing loss is a common affliction of age and toxic drugs. The cortex adapts to such loss by altering excitatory and inhibitory inputs to neurons, and by expanding the cortical representation of the “edge” of the cochlear lesion without elevating the activation threshold. This implies an active and dynamic process of reorganization - one that must be continuously engaged in the normal brain to also account for the effects of use and learning.

A theoretical understanding of learning lies at the heart of understanding intelligence. Peter Dayan and Angela Yu examine the ways in which uncertainty controls learning. Many theoretical models of learning focus exclusively on error and ignore uncertainty. Dayan and Yu review the links between learning and uncertainty from three perspectives: statistical theories such as the Kalman filter; psychological models, in which differential attention is paid to stimuli with an effect on the speed of learning associated with those stimuli; and neurobiological data on the influence of the neuromodulators acetylcholine and norepinephrine on learning and inference.

Uncertainty is often manifest as noise, but noise can also enhance signals. Prasun Kumar Roy and D. Dutta Majumder explore how stochastic resonance can explain many cognitive phenomena. To the scientist or engineer, perturbation or noise has traditionally been regarded as a nuisance, and efforts are usually made to minimize the noise. However, the recent discovery of noise-activated ordering or enhancement shows that under certain circumstances, noise can in fact help the performance of systems. This is, in some sense, the antithesis of the motivation for Kalman filtering. Roy and Majumder show that stochastic activation dynamics occur in the brain, ensuring cognitive enhancement, and that this can happen in various phases of sleep cognition. They examine concepts such as dream and lucidity from both quantitative and experimental approaches. Noise-enhanced information processing systems may furnish a new template for designing neuroengineering based computing machines.

Stochastic resonance is a form of nonlinear dynamics, which is key to understanding brain processing and the creation of emergent outputs. Artificial neural network models typically assume that the synapses are linear. This assumption is not well founded in biological fact, but serves to simplify the analysis and design of artificial neural networks for a variety of tasks, including learning and optimization. Jayadeva, Kamlesh Kumar Pathak and Arindam Chakraborthy consider a new form of pulse coupled neural network, where synaptic action is comprised of two components: a nonlinear action which depends on both pre-synaptic and post-synaptic activity levels, and a linear component which is associated with the post-synaptic circuitry alone. They show that networks comprising such neurons can be used to efficiently solve difficult optimization problems. Such tasks may arise in the processing of signals in the auditory and visual pathway, but the proposed approach can be used for other applications as well.

In sum, the papers in this Special Issue represent a rich assortment of ideas that characterize experimental and theoretical approaches to the brain and mind. We hope that these papers will provide a stimulating introduction to Cognitive Science to readers of the IETE Journal of Research. We thank IETE for providing us the opportunity to organize this issue. Last but not least, we thank the authors for their contribution.

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