

Introduction

About half a century ago, the first micro-electrode recordings of sensory neurons in mammalian visual cortex transformed our thinking about how vision works. Since that time, the physiology of cognitive processes has developed into a mature and complete discipline. New techniques have been developed and the old techniques are being deployed in new ways. However, the most spectacular development has been the growth in the range of topics that are now addressed by this discipline.

Recording with micro-electrodes is still at the centre of the stage, but its application is no longer restricted to anaesthetized, paralysed animals. Today neurons can be studied in awake animals that are looking, learning, remembering and making decisions. Non-invasive techniques, such as functional magnetic resonance imaging (fMRI) of the brain and measurement of scalp potentials, are constantly being developed and improved. Therefore we can now also approach the study of the physiology of cognition in the intact human brain.

Lesions are still used to study the location of function in the brain. But today they are much more subtle and selective than before. Now they may disconnect structures, so that interactions can be studied, rather than removing or destroying them. Destruction may be selective for cell bodies, or for a particular type of cell body, so that fibre tracts can be spared. Again, imaging techniques have greatly improved the precision of this approach with human subjects.

The papers in this issue form the record of a Discussion Meeting on the physiology of cognitive processes that was held in December 2001. The topics include sensation, perception, decision making, attention, memory, the application of rules to guide our behaviour and the use of sensory information to control our movement. To deepen our understanding of leading-edge technology, we also have two papers of a more technical nature dealing with operation of visual cortex: one on the nature of neural codes in visual cortex and the other on the neural correlates of the fMRI bold signal.

One of the most basic questions one can ask about a perceptual process is 'where in the brain does it take place?' Brian Wandell and his colleagues (Wade *et al.* 2002) addressed this question in the case of colour vision, using fMRI in the human brain.

Cortical colour areas in the human brain can be identified by their responses to colour stimuli in fMRI and by the characteristic form of the cortical map of the visual field. Cortical signals for colour have an expanded representation for the central zone of the retina, because this zone has a fundamental role in the generation of colour perception. The ventral surface of the occipital lobe has

been identified on the basis of lesion studies as an important area for human colour vision. The paper by Wade *et al.* describes visual field mapping of the ventral surface of the occipital lobe with fMRI. One novel finding is a full map of the contralateral half of the visual field adjacent to V3, which these authors regard as the human equivalent of V4. They also identified a further partial or fragmented map, which includes substantial parts of central visual field. Both these areas give strong responses to colour signals.

Derrington *et al.* (2002) consider whether colour analysis by the visual system always operates to identify colours or whether the importance of colour may be that it supports image segmentation. They showed that, even for a primate species with relatively poor colour vision (the marmoset), colour is a fundamental attribute of visual stimuli. Male marmosets, all of which are dichromats, rapidly learn to distinguish coloured from non-coloured stimuli. A proportion of neurons in visual cortex respond in a way that distinguishes between the presence and absence of colour, regardless of which particular colour is present.

To interpret the significance of variations in the firing of visual neurons we need to know the nature of the neural code. Usually the assumption is that it is a very simple code. Oram *et al.* (2002) consider a more sophisticated range of possibilities. The paper reviews the way information is encoded by neurons in monkey visual cortex and considers whether neurons could carry multiple signals concurrently.

A more pressing issue concerning interpretation arises in the case of fMRI, which is widely used to chart the activity associated with perceptual and cognitive processes in the human brain. Critically, however, the link between neural activity and the haemodynamic responses that are monitored by fMRI has not been established. Logothetis (2002) sets this right in his paper, which is a technological *tour de force*. He describes simultaneous micro-electrode and fMRI measurements, in which he compares the fMRI signal with local field potentials, which represent the synaptic activity in a brain region, and with spiking activity, which represent the output. The better prediction of the fMRI responses is given by local field potentials, which suggests that much of the fMRI response represents the neural processing within a cortical area rather than the output from that area.

The somatosensory system is the subject of a highly sophisticated study of sensory processing in which Ranulfo Romo and his colleagues (Romo *et al.* 2002) use micro-electrode recording to track the elements of a sensory discrimination process across several cortical areas in the monkey. Their paper shows that neurons in primary somatosensory cortex (S1) generate sensory representations of vibrating tactile stimuli; neurons in two other areas, the second somatosensory area (S2) and medial premotor cortex, appear to display the memory of the stimulus and to

One contribution of 14 to a Discussion Meeting Issue 'The physiology of cognitive processes'.

compare it with subsequent stimuli as the monkey makes decisions about them.

Sensory decisions are also the topic of the paper by Parker *et al.* (2002), who seek to identify the neural events that underlie decisions about ambiguous visual stimuli. A monkey is faced with a task of deciding the direction of rotation of a cylindrical surface that rotates about an axis perpendicular to his line of sight. To make the judgement he needs to assign different depths to two fields of dots moving in opposite directions. Most of the stimuli he views are unambiguous because he has independent sensory information—stereopsis—to assign depths to the dots. By analysing how neurons in the cortical V5/MT area—which are selective both for stereoscopic depth and for direction of motion fire in response to ambiguous and non-ambiguous stimuli, and by analysing the correlation between neuronal firing and the monkey's decisions on ambiguous stimuli they are able to infer which neurons influence the monkey's decision.

Maunsell & Cook (2002) also describe responses to motion by neurons in the cortical V5/MT area and compare them with neurons in the VIP area. They examine how attention modulates sensory performance and neural firing in the two different areas. They track the influence of attention both on a monkey's ability to perform visual discriminations and on the responses of visual neurons. Attention generally increases neuronal responsiveness and improves behavioural performance, but to different degrees. Moreover the effect of attention on neural responsiveness is different for different areas with some brain areas showing larger neuronal effects of attention than the improvement in behavioural performance. They conclude that, in most cortical areas, links between neural activity and sensory discrimination may vary with attentional state.

In many natural situations, when we shift attention to an object we make a saccade to fixate on it. In his paper, Schall (2002) discusses the neural processes that select which targets the eyes will fixate during a search task and the processes that produce the eye movement that changes fixation. He shows that different neurons control the selection of targets to be fixated and the production of saccades to fixate those targets. He points out that only by separating target selection from saccade production can the system be flexible.

The first of three papers on memory considers the neural substrate of recognition memory. One of the important processes of recognition memory is the discrimination between what is novel and what is familiar. In their paper, Brown & Bashir (2002) discuss evidence that neurons in the perirhinal cortex of the temporal lobe respond when a stimulus is novel, but not if the monkey has seen it before. They show that selective failure to respond to familiar stimuli can be the basis of an efficient memory storage system and that long-term synaptic depression is a form of neural plasticity that might be the basis of such a system.

In the second paper on memory Rugg *et al.* (2002) describe their recent investigations of the encoding and retrieval of memories for events using non-invasive neuroimaging techniques in humans. Encoding events in memory appears to involve the same brain regions that process those events online. Retrieval appears to involve lateral

parietal cortex and regions of dorsolateral and anterior prefrontal cortex.

In his paper, Gaffan (2002) argues persuasively against the widely accepted idea that the temporal lobe contains specialized memory systems. This idea is based on the fact that memory deficits are often associated with damage to the temporal lobe in humans and damage to the temporal lobe in monkeys may also cause amnesia. However Gaffan points out that temporal cortex has perceptual functions and that amnesia can be produced by disconnecting the temporal lobe from the brainstem and basal forebrain. He suggests that memories are likely to be widely distributed in cortex, particularly prefrontal cortex.

The paper by Miller *et al.* (2002) describes recordings from single neurons in prefrontal cortex in monkeys that are classifying stimuli according to arbitrary rules. A substantial proportion of neurons in monkey prefrontal cortex appear to represent the rules that the monkey follows for categorizing visual stimuli. When the monkey is trained to classify the same stimuli in new ways, the responses of the neurons reflect the newly learned categories, not the old ones. In a task where the monkey has to switch rules from trial to trial, individual prefrontal cortex neurons appear to fire according to which rule is in place on a particular trial.

In the final paper, Daniel Wolpert and colleagues (Van Beers *et al.* 2002) discuss three aspects of the way variability in neural signals limits our ability to control our movements. First, variability of sensory signals limits our knowledge of the position of the parts of our bodies. These inaccuracies may be different for different senses, such as proprioception and vision. The brain integrates signals from different senses to make the best estimate of position. Second, variability of neural signals to control the muscles produces further inaccuracies, but movements are planned so as to minimize the errors caused by these inaccuracies. Finally, motor signals have to be integrated with sensory signals to predict current disposition of the body, particularly its limbs. The paper considers theoretically how this integration should be best achieved.

The underlying theme of all the papers is to understand the neuronal events and processes that are responsible for the remarkable range of cognitive performance that can be achieved. The meeting represented some of the major components of this theme, with a particular emphasis on current advances. The next 10 years will no doubt see the transformation of this knowledge in specific areas. However, such transformations will come about chiefly through the continued application of the unified approach that is represented by this sample of work.

The editors would like to thank Froniga Lambert and her colleagues for their expert assistance during the organization of the meeting and Ruth Hinkel-Pevzner for her unswerving dedication to meeting deadlines during the editing of this set of papers. They also thank Helen Winsor, Jessica Mnatzaganian and Michelle McNeely for so ably seeing the issue through to press.

Andrew Parker¹

Andrew Derrington²

Colin Blakemore¹

April 2002

¹Laboratory of Physiology, University of Oxford, Parks Road, Oxford, OX1 3PT, UK

²*School of Psychology, University Park, University of Nottingham, Nottingham, NG7 2RD, UK*

REFERENCES

- Brown, M. W. & Bashir, Z. I. 2002 Evidence concerning how neurons of the perirhinal cortex may effect familiarity discrimination. *Phil. Trans. R. Soc. Lond. B* **357**, 1083–1095. (DOI 10.1098/rstb.2002.1097.)
- Derrington, A. M., Parker, A., Barraclough, N. E., Easton, A., Goodson, G. R., Parker, K., Tinsley, C. J. & Webb, B. S. 2002 The uses of colour vision: behavioural and physiological distinctiveness of colour stimuli. *Phil. Trans. R. Soc. Lond. B* **357**, 975–985. (DOI 10.1098/rstb.2002.1116.)
- Gaffan, D. 2002 Against memory systems. *Phil. Trans. R. Soc. Lond. B* **357**, 1111–1121. (DOI 10.1098/rstb.2002.1110.)
- Logothetis, N. K. 2002 The neural basis of the blood-oxygen-level-dependent functional magnetic resonance imaging signal. *Phil. Trans. R. Soc. Lond. B* **357**, 1003–1037. (DOI 10.1098/rstb.2002.1114.)
- Maunsell, J. H. R. & Cook, E. P. 2002 The role of attention in visual processing. *Phil. Trans. R. Soc. Lond. B* **357**, 1063–1072. (DOI 10.1098/rstb.2002.1107.)
- Miller, E. K., Freedman, D. J. & Wallis, J. D. 2002 The prefrontal cortex: categories, concepts and cognition. *Phil. Trans. R. Soc. Lond. B* **357**, 1123–1136. (DOI 10.1098/rstb.2002.1099.)
- Oram, M. W., Xiao, D., Dritschel, B. & Payne, K. R. 2002 The temporal resolution of neural codes: does response latency have a unique role? *Phil. Trans. R. Soc. Lond. B* **357**, 987–1001. (DOI 10.1098/rstb.2002.1113.)
- Parker, A. J., Krug, K. & Cumming, B. G. 2002 Neuronal activity and its links with the perception of multi-stable figures. *Phil. Trans. R. Soc. Lond. B* **357**, 1053–1062. (DOI 10.1098/rstb.2002.1112.)
- Romo, R., Hernández, A., Zainos, A., Brody, C. & Salinas, E. 2002 Exploring the cortical evidence of a sensory-discrimination process. *Phil. Trans. R. Soc. Lond. B* **357**, 1039–1051. (DOI 10.1098/rstb.2002.1110.)
- Rugg, M. D., Otten, L. J. & Henson, R. N. A. 2002 The neural basis of episodic memory: evidence from functional neuroimaging. *Phil. Trans. R. Soc. Lond. B* **357**, 1097–1110. (DOI 10.1098/rstb.2002.1102.)
- Schall, J. D. 2002 The neural selection and control of saccades by the frontal eye field. *Phil. Trans. R. Soc. Lond. B* **357**, 1073–1082. (DOI 10.1098/rstb.2002.1098.)
- Van Beers, R. J., Baraduc, P. & Wolpert, D. M. 2002 Role of uncertainty in sensorimotor control. *Phil. Trans. R. Soc. Lond. B* **357**, 1137–1145. (DOI 10.1098/rstb.2002.1101.)
- Wade, A. R., Brewer, A. A., Rieger, J. W. & Wandell, B. A. 2002 Functional measurements of human ventral occipital cortex: retinotopy and colour. *Phil. Trans. R. Soc. Lond. B* **357**, 963–973. (DOI 10.1098/rstb.2002.1108.)