Paradoxical activities: insight into the relationship of parietal and prefrontal cortices

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What are the functions of the parietal and prefrontal cortices and how do these regions interact to achieve their objectives? How does context change plans for action? Are 'visual' and 'motor' well-defined attributes of neuronal activity in the association cortex? Recent studies of the saccadic system in monkeys have revealed two sets of paradoxical data: in parietal cortex, activity has visual timing but motor direction; in prefrontal cortex, activity has motor timing but visual direction. Analyzing the prefrontal and parietal data together leads to surprising insights. It appears that these paradoxical activities are intermediates in a parietal–prefrontal–parietal loop that has a rapid turnaround, and that a possibly prefrontal context-contingent signal switches sensorimotor transformations in parietal cortex.

Traditional views of cortical functional architecture associate sensory, perceptual functions with the parietal cortex, and motor, executive functions with the frontal cortex, but do not specifically address the interaction of the two lobes. These views are challenged by recent data showing that many cognitive functions activate both lobes. This article discusses two studies of sensorimotor processing in the well-defined saccadic system that report paradoxical activities, appearing to be visual in one way and motor in another. The paradoxical activity in the parietal lobe differs from that in the prefrontal. This article presents three seemingly unrelated issues and goes on to describe their paradoxical activities and implications. It concludes by presenting a hypothesis that might explain these paradoxical activities, linking the three issues together. Owing to space restrictions, only the most relevant aspects of each issue are considered and only the most directly relevant work is cited.

Three issues relating to the functions of the parietal and prefrontal cortices in sensorimotor processing

Functional relationship of parietal and prefrontal cortices

This article focuses on cortical processing of saccadic eye movements, as studied with memory-saccades (Boxes 1,2), particularly in the lateral intraparietal (LIP) area [1–25] and in dorsolateral prefrontal areas 46 and 8a [26–39]. With a single exception, other areas in these lobes are not discussed, even though the conclusions made probably hold beyond LIP and 46. Area LIP and areas 46 and 8a are involved in working memory, which, for many years, was thought to be a predominantly prefrontal function. Goldman-Rakic and colleagues compared the activity recorded from the LIP and 8a areas of monkeys performing memory-saccades [7] and found a striking similarity between the two areas. This might suggest that sustained memory activity in LIP merely mirrors that of the prefrontal sustained activity. However, this was not the case because the investigators inactivated one of these areas while recording from the other [8]. Activity in LIP was not abolished by cooling prefrontal cortex; it was slightly impaired, but so was the activity in 8a when the parietal cortex was cooled. Do these similar patterns of activity mean that both areas have the same functions? Are the neuronal responses of the two areas similar in all tasks?

Consistency of neuronal responses as 'visual' or 'motor'

'Visual' and 'motor' are well-defined properties of neuronal activity in the periphery. But are they also well defined in high-level association cortex? Here, there are two issues to consider. First, massive recurrent connections make it difficult to associate activity in association cortex with the anatomically remote periphery. Second, activity in association cortex might be related to perception and attention [9,18,40–42] as much as it is to sensation; to motor plans that can be changed [6] as much as to irrevocable commands; and to working memory [7,8,27,28,43] as much as to immediate processing. These issues do not rule out the possibility of making sense of 'visual' and 'motor' properties in association cortex but they highlight the need for rigorous testing of whether these properties are well defined.

Two methods are used to establish whether activity is visual or motor. The first works by dissociation in space [44] and the second by dissociation in time [3,4,11,45] (Box 2). That there are two standard dissociation procedures brings up the question of whether the results of these procedures are consistent with each other. If visual and motor activity are well defined, all neurons will be consistently classified as visual or as motor (or both). It is possible to test dissociations in time and space using a

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Box 1. Some paradigms for studying sensorimotor and cognitive processing related to saccades

When we look around a stationary scene, our eyes briefly fixate a series of spots. The fixations are separated by specialized jumps of the eyes, called saccades. Fixation and saccades are used in laboratory tasks that implicate specific cognitive operations. Figure Ia illustrates and explains the tasks relevant for this paper. Figure Ib shows the 'mixed task', which is configured relative to the response field of the neuron being studied, and used to determine whether its activity is visual or motor.

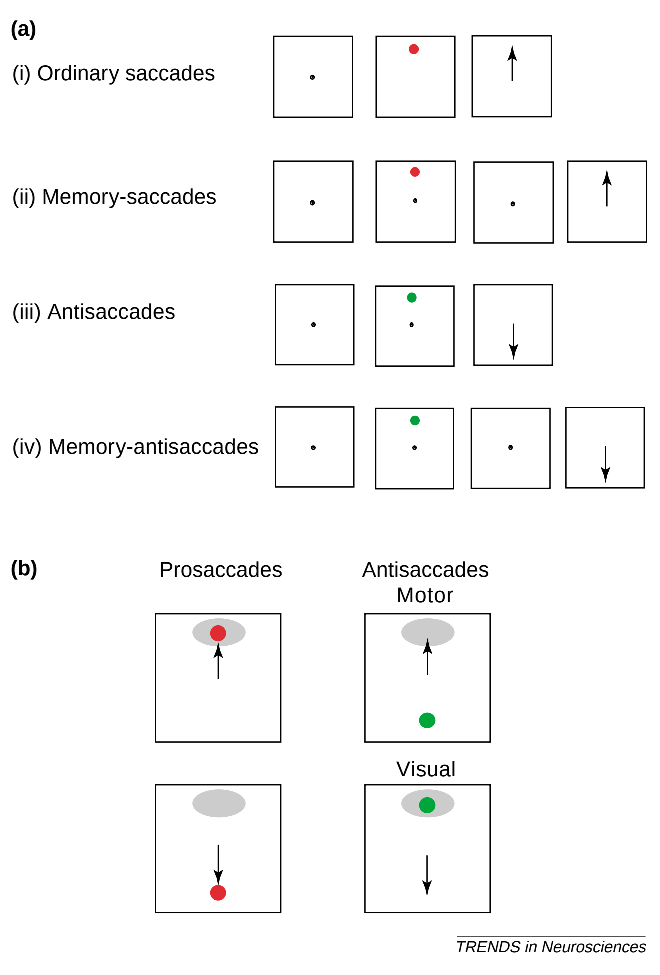

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Figure I. Saccade tasks. **(a)** Sequence of visual stimulation (black, red and green spots) in the different trial types and the saccades eventually required (arrows in rightmost panels). (i) The basic ordinary saccadic eye movements task begins with the subject directing his or her line of gaze towards a fixation spot (black); when the spot 'jumps' to another location, the subject follows the jump with a saccadic eye movement. The saccade usually begins within 0.25 s after the jump of the target ('saccadic latency'). The sequence of visual events is stimulation by a central fixation spot and then a red target (here drawn upwards from the fixations spot), followed by the required saccade (arrow in the third panel). (ii) In memory-saccades (also called memory-prosaccades), the fixation spot remains while a target flashes at a peripheral location (red spot above fixation spot in second panel). The subject cannot look at the target at this time, but instead must continue to gaze at the fixation spot during the memory period, after the target disappears (third panel); only after the fixation spot turns off can the subject look at the remembered position of the target. (iii) In antisaccades, instead of looking toward the green target, the subject must look at the opposite location (inverse vector). (iv) Memory-antisaccades are a merge of memory-saccades and antisaccades. After the memory period (third panel), the subject must look at the opposite location from that where the target had been. **(b)** Four trial types of the mixed (mixed memory-prosaccade, memory-antisaccade task) task. The gray ellipse illustrates the response field of the neuron being studied. The target appears in one of two opposite locations (here drawn as either upwards or downwards arrows), which are kept constant during a block. A contextual cue (here, the target color) informs the subject whether the current trial requires a memory-prosaccade (red target) or a memory-antisaccade (green target). Target color is a useful cue in cortical areas with neurons largely insensitive to color, such as those in the lateral intraparietal area of the dorsal visual stream. During recording of neuronal activity, the mixed task is run after the response field of the neuron had already been mapped. The two possible target locations are chosen so that one location falls in the response field, the other outside it. Memory-antisaccade trials of the mixed task fall into two groups. 'Visual memory-antisaccades' have the target falling in the response field and the movement made away from the field (bottom right); 'Motor memory-antisaccades' have the opposite configuration (top right). These names reflect the procedure of using antisaccades to dissociate visual activity from motor activity in space Box 2. Neurons with visual activity would be active in visual memory-saccades and inactive in motor memory-antisaccades; neurons with motor activity would be active in motor memory-antisaccades and inactive in visual memory-antisaccades.

mixed memory-prosaccade, memory-antisaccade task, for short, the 'mixed task' (Box 1).

Context switching of sensory to motor transformations

The actions of humans are profoundly influenced by understanding that transcends immediate sensory stimuli. For example, our response to the view of an approaching lion is likely to be influenced by a contextual signal, such as whether the cage door has been left open, or by *a priori* knowledge, such as the existence of a transparent separating wall. The actions of a football player depend not only on the position of the other players but also on an interpretation of their intentions. The mixed task provides a laboratory model for studying the effect of context by instructing the animal to switch between regular saccades and antisaccades (Box 1); Figure 1 proposes a view of the implicated information processing. The image of the target is processed by two parallel streams. The main stream transmits the location of the target to a 'sensorimotor transformation module', which is set by default to a prosaccade configuration. In antisaccade trials, a switching signal must arrive at the sensorimotor transformation module and instruct it to switch to the antisaccade configuration. The monkey uses contextual information (target color [25] or the shape of the fixation spot [46]) to determine the task and compute the switching signal. The brain process that computes the switching signal from the visual input is the 'context-recognition module'. However, it is not clear where context recognition is located in the brain, how it categorizes contexts, or how the signal switches the sensorimotor transformation.

Visual, motor and paradoxical activity

Consistent activity

Most of the activity in LIP and areas 46 and 8a can consistently be classified as visual or motor. The neuron shown in Figure 2a responds in those trials in which the response field is visually stimulated (Figure 2a,i,iv), but not in the other trials. Thus, dissociation by space classifies this neuron as visual. The vigorous response of the neuron starts shortly after the target appears and tapers off when the target disappears. Therefore, dissociation by time also classifies this neuron as visual. The neuron shown in Figure 2b is consistently motor. It responds in

Box 2. Methods for dissociation of visual and motor responses

The dissociation problem

Figure Ia illustrates the activity of a schematic neuron during a saccadic eye movement. Is this activity motor, reflecting preparation of the saccade, or visual activity, reflecting a sensory response to the image of the target? The saccade made in Figure Ia(i) is into the response field of the neuron. The neuron is inactive during a saccade in the opposite direction (Figure Ia,ii).

Dissociation in time

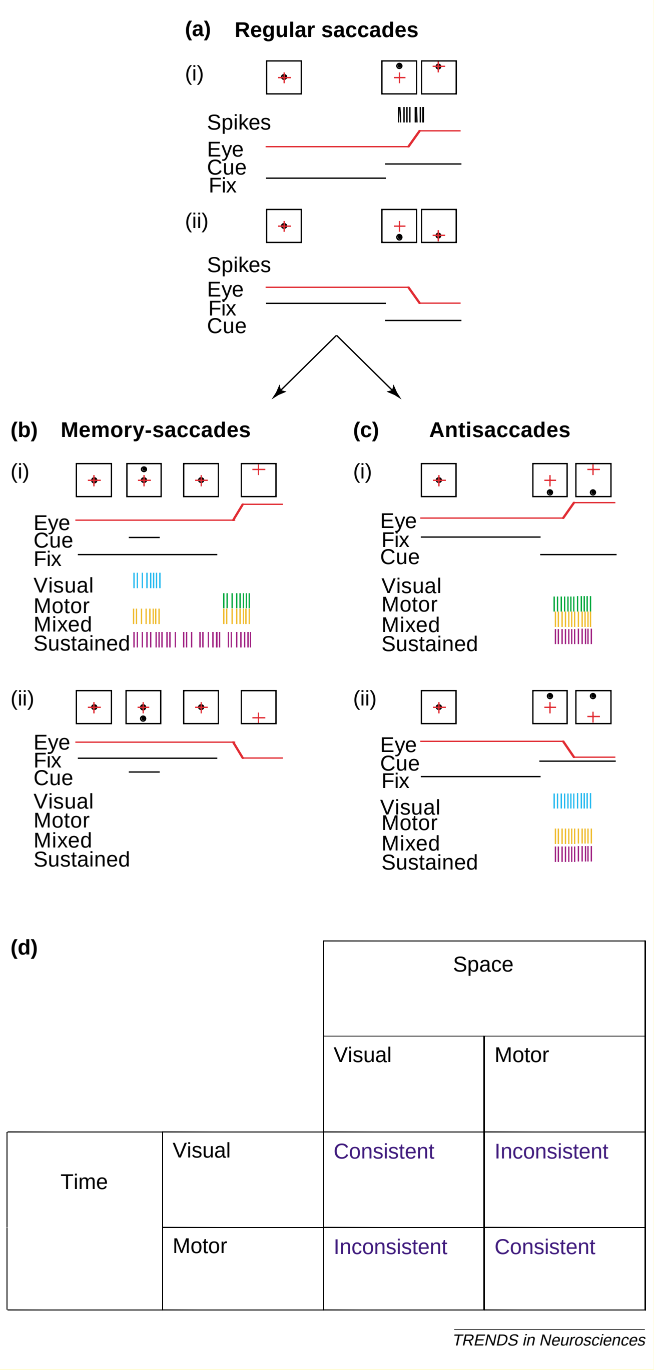
The neuron is then tested while the monkey performs memory-saccades (Figure Ib). If the activity in Figure Ia(i) is visual, the activity in Figure Ib(i) would be that in blue: the neuron fires shortly after stimulus onset but not at the time of the movement. If the activity in Figure Ia(i) is motor, the activity in Figure Ib(i) would be that in green: activity occurs before and during the saccadic eye movement but not at the time of the stimulus. Memory-saccades sometimes show that a response is both visual and motor (orange), or even that a neuron remains active during the memory period (violet). The neuron remains inactive on memory-saccades in the opposite direction (Figure Ib,ii).

Dissociation in space

In Figure Ia(i), both visual stimulus and saccadic movement are directed upwards, into the response field of the schematic neuron. Only the movement is directed into the response field in of the neuron in Figure Ic(i) (motor antisaccades); only the stimulus falls in the response field on the neuron in Figure Ic(ii) (visual antisaccades). Hence, if the activity in Figure Ia(i) is visual, the neuron will be active in visual, not in motor, antisaccades (blue); if the activity is motor, the neuron would be active in motor but not visual, antisaccades (green).

Consistency table

If neurons were to be tested in both dissociation procedures, the results would fall in a consistency table (Figure Id). Note that two entries in this table stand for consistent dissociations, and two entries for inconsistent results. Inconsistent results would cast doubt on whether ‘visual’ and ‘motor’ are well defined.



		Space	
		Visual	Motor
Time	Visual	Consistent	Inconsistent
	Motor	Inconsistent	Consistent

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Figure I. The dissociation problem. Schematic trials illustrating the dissociation problem **(a)** and its two solutions **(b,c)**. Each panel shows, from top to bottom: the stimulus sequence (black) and superimposed eye position (red cross); spike rasters (various colors); eye position (red); and stimulus traces as functions of time (black). Each color of the spike rasters in (b) and (c) reflects a possible pattern of activity; all these patterns are consistent with the activity in (a). **(d)** Table summarizing how the results of dissociation in time and dissociation in space could be either consistent or inconsistent for visual and motor activity.

trials in which a saccade is planned towards the response field of the neuron (Figure 2b,i,ii), and it is active not during the presentation of the visual target but later, peaking close to the time of the saccade.

Paradoxical activity in parietal cortex

Some neurons in the parietal and prefrontal cortices show paradoxical activity, reflecting an apparent inconsistency between the two dissociations of visual and motor activity

(Figure 2c,ii,d,iv). Many LIP neurons appear to be visual because they are active in trials where the response field is visually stimulated by the target, with typical visual timing (Figure 2c,i,iii,iv). Yet the activity shown in Figure 2c (ii) cannot be visual because the target falls outside the response field. Of the neurons classified as visual by dissociation in time, approximately one-third show this added activity in memory antisaccades. These are motor memory-antisaccades – the monkey is planning a movement into the response field of the neuron and, thus, dissociation by space classifies the activity as motor. However, dissociation by time classifies this activity as visual because the timing of the response is similar to the timing of the responses in the visual conditions (Figure 2c,i,iv) and very different from the timing of the motor response (Figure 2b,i,ii).

In memory-antisaccade trials there are two waves of activity traveling through LIP (Figure 3): a first wave of bottom-up visual responses and, ~50 ms later, a slightly smaller wave of paradoxical activity. The two waves activate mutually exclusive populations of LIP neurons with opposite response fields.

This paradoxical activity appears to reflect an inconsistency between the two dissociations of visual and motor activity. The 2 × 2 consistency table in Figure 4 shows that this paradoxical activity falls into an inconsistent entry.

Paradoxical activity in prefrontal cortex

In 1993, Goldman-Rakic and collaborators used the mixed task to study dorsolateral prefrontal cortex [46]. The task used a different contextual cue (fixation-spot shape) to that in the study by Zhang and Barash (target color). The activity of the prefrontal neuron in memory-prosaccades is marked by persistent activity that continues until the time the saccade is made (Figure 2d,i). Dissociation by space classifies this build-up as visual because the neuron is very active in visual memory-antisaccades (Figure 2d,iv) and inactive in motor memory-antisaccades (Figure 2d,ii). However, dissociation by time classifies the activity as motor because vigorous build-up activity begins almost 1 s after the visual stimulation ends, and the build-up increases towards, and peaks at about, the time of the saccade (Figure 2,iv). Approximately two-thirds of the sustained activity neurons in area 46 show this paradoxical pattern of activity [46].

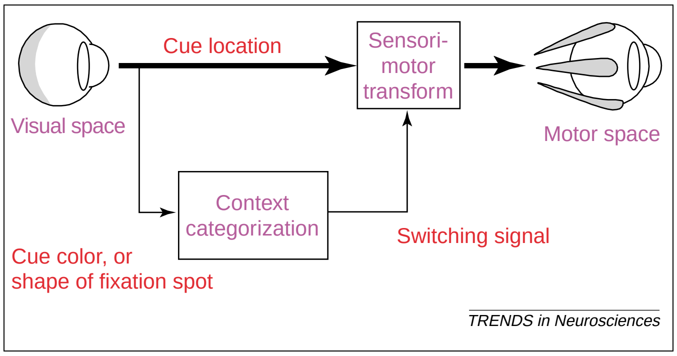

Figure 1. Proposal for the Information flow required for performing the mixed task. Two parallel streams of information involve two presumed modules: one for sensorimotor transformations, the other for context categorization. ‘Visual space’ denotes the range from retina to mid-level extrastriate visual areas that feed into the lateral intraparietal area and subsequently prefrontal cortex. ‘Motor space’ denotes saccadic centers downstream, superior colliculus to oculomotor plant. To perform antisaccades, contextual information (cue color in Box 1) must be used to identify the current trial as a memory-antisaccade, and a command has to switch the sensorimotor transformation module to the antisaccade configuration. This is the function of the presumed ‘context-categorization’ module.

Visual and motor activities are well defined

Considered separately, each form of paradoxical activity appears to reflect an inconsistency between the two dissociations of visual and motor activity. The 2 × 2 consistency table in Figure 4 shows that the paradoxical activities fall into the inconsistent entries. However, if visual and motor classifications are arbitrary and do not reflect the actual properties of neuronal activity, the 2 × 2 consistency table should be filled-in uniformly, both by parietal and prefrontal activity. However, this does not happen. Intriguingly, all seemingly inconsistent activity from parietal cortex falls into one inconsistent entry of the table and all seemingly inconsistent activity from prefrontal cortex falls into the other inconsistent entry. Thus, considered together, the paradoxical activities are unlikely to truly reflect inconsistency. Rather, they probably reflect specific intermediate states (as will be discussed). That all other activity falls into the consistent entries of the consistency table supports the view that visual and motor responses are well-defined properties of activity even in association cortex.

Implications of the paradoxical activities for sensorimotor processing in cortex

The hypothesis that follows takes on a formal, algebraic-like approach; that is, the patterns of activity shown in Figures 2 and 3 are a metaphoric equation and the solution to the equation should be a circuit.

The parietal and prefrontal paradoxical activities differ in two ways. First, prefrontal paradoxical activity replaces the activity expected in motor memory-antisaccades: neurons are active in two of the four conditions of the mixed task (Figure 2d). By contrast, parietal paradoxical activity adds to the activity expected in visual memory-antisaccades: neurons are active in three conditions in the mixed task (Figure 2c). Second, the latency of the parietal paradoxical activity is slightly higher than that of the visual response (Figure 3); no similar difference is evident for the prefrontal paradoxical activity. Any explanation of the paradoxical activities must also explain these differences.

Two mechanisms could account for the parietal paradoxical activity. Paradoxical activity might be re-entrant activity, reflecting activation by recurrent connections probably from other parts of the brain [47]. Alternatively, as suggested by Schlag-Rey *et al.* [48], the paradoxical activity might be a visual response to stimulation of a non-standard visual receptive field. While the monkey trains to perform antisaccades, receptive fields of some visual neurons might be modified such that, in antisaccade trials, they respond to visual stimuli in the position opposite that of the target. The time-course of mean paradoxical activity is consistent with this hypothesis

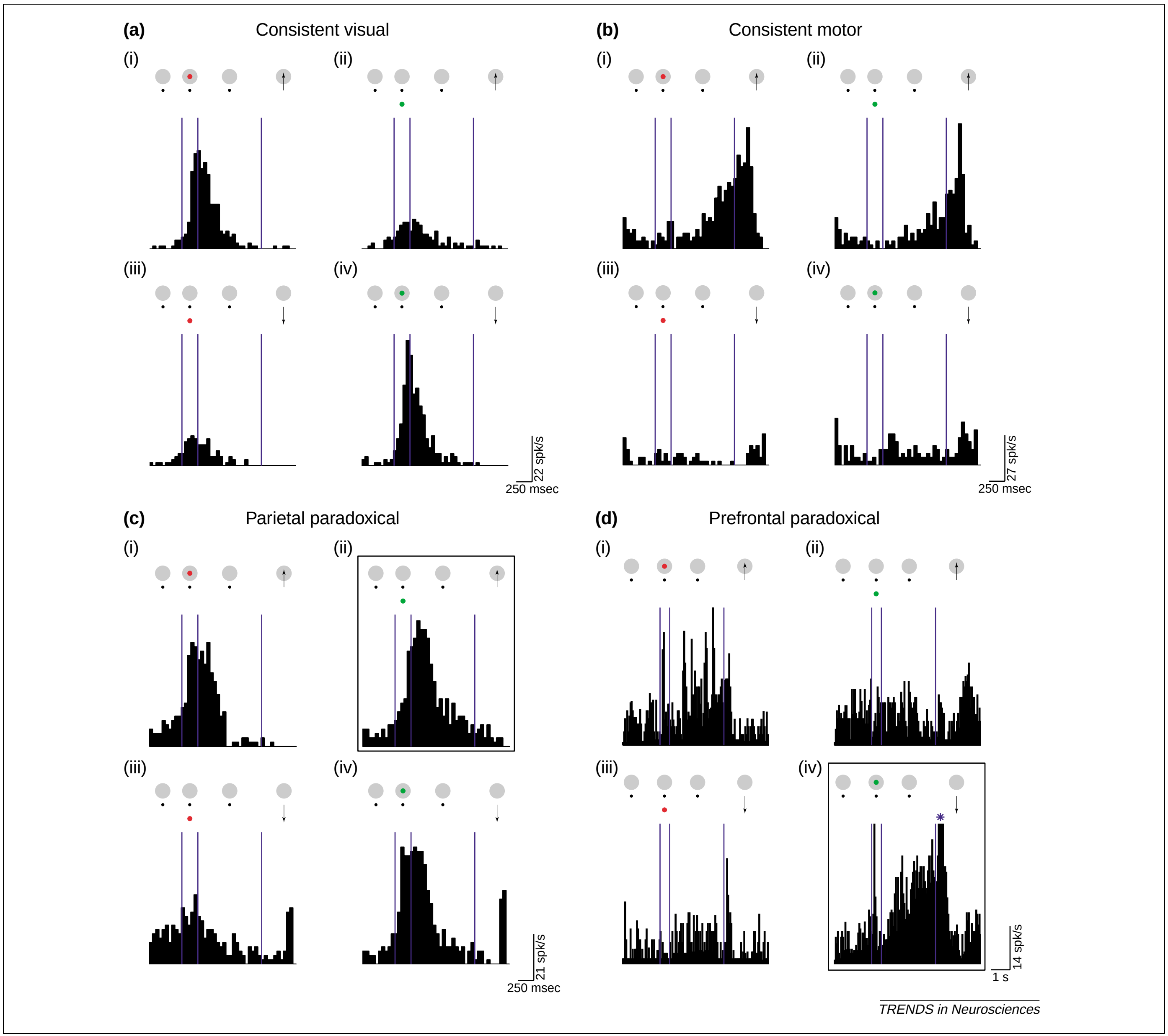

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Figure 2. Two neurons with consistent activity **(a,b)** and two neurons with inconsistent (paradoxical) activity **(c,d)** recorded from monkeys performing the mixed task. Each group of four panels shows the four trial types, in the same arrangement as in Figure Ib of Box 1: the leftmost two panels (i,iii) reflect memory-prosaccades and the rightmost two panels (ii,iv), memory-antisaccades. Each panel includes a schematic illustration of the task and a post-stimulus time histogram showing the activity of the neuron in that task. The vertical lines show, from left: onset of the target, offset of the target and offset of the fixation spot, which signals the monkey to make the saccade (Box 1). The neuron with consistently visual activity (a), neuron with consistently motor activity (b) and neuron with parietal paradoxical activity (c) were recorded in the lateral intraparietal area [25]. The neuron with prefrontal paradoxical activity (d) was recorded in area 46 [46]. The conditions of the paradoxical activities (c,ii and d,iv) are emphasized. Note that the peak of the response in d(iv) is clipped (marked by the blue plus sign). Panels (a–c) reproduced, with permission, from Ref. [25] © (2000) Macmillan Magazines Ltd (http://www.nature.com/); (d) reproduced, with permission, from Ref. [46], © (1993) Macmillan Magazines Ltd (http://www.nature.com/).

(Figure 3): after the slightly longer latency (~50 ms), mean paradoxical activity increases to values similar to those of the mean visual responses. The slightly longer latency of the paradoxical activity could reflect switching – the time necessary for changing the response field of the neuron to its antisaccade configuration.

Regardless of whether the paradoxical activity is non-standard visual response or re-entrant activity, one thing is clear: the paradoxical activity occurs only in trials recognized to be memory-antisaccades. The parietal paradoxical activity depends on the availability of a switching signal. That the parietal paradoxical activity begins shortly after the visual response shows that the switching signal is made available to the parietal cortex rapidly.

However, a word of caution is necessary. The two paradoxical activities were observed in independent studies using slightly different procedures and different monkeys. Rigorous testing of the hypothesis offered in this article (see later) must begin by recording the two paradoxical activities using the same procedure and from the same monkey.

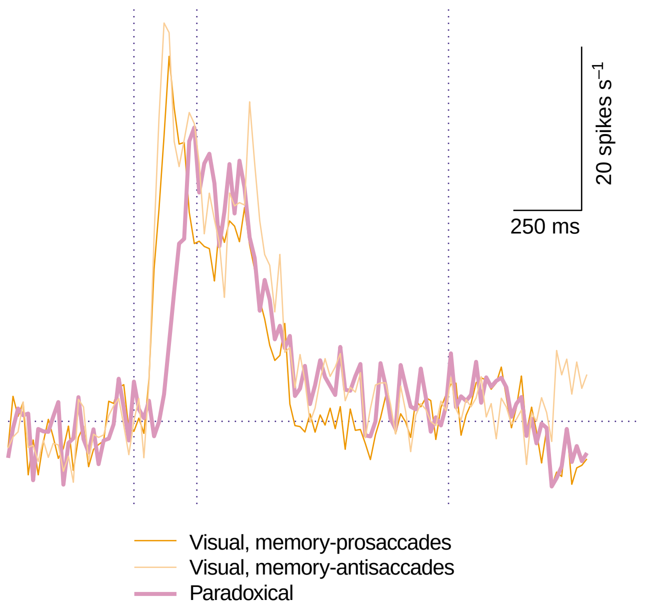

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Figure 3. Comparison of the mean paradoxical activity of 56 neurons (purple trace) with the visual responses in memory-prosaccades and in memory-antisaccades (orange traces) of the same neurons. Activity in the baseline condition of memory-prosaccades opposite the response field was subtracted. The mean paradoxical activity is marked by an abrupt onset similar to that of the visual response but with increased latency (~50 ms difference). Reproduced, with permission, from Ref. [25], © (2000) Macmillan Magazines Ltd (http://www.nature.com/).

		Space	
		Visual	Motor
Time	Visual	Consistent	Parietal paradoxical
	Motor	Prefrontal paradoxical	Consistent

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Figure 4. Consistency table. When activity is tested in memory-saccades and memory-antisaccades, the results of its two dissociations in space and in time can be fitted into a 2 × 2 consistency table. The two entries along the main diagonal are the consistent entries. Neurons that are truly visual or truly motor would be assigned to one of these entries. Neurons that are truly both visual and motor would be assigned to both two consistent entries. Thus, consistency of the two dissociations would be supported if, after classifying many neurons, both inconsistent entries were empty. The inconsistent entries do not remain empty but they are anatomically segregated. Activity falling into the inconsistent category is termed paradoxical. Most or all prefrontal paradoxical activity falls into one inconsistent entry and virtually all parietal paradoxical activity into the other inconsistent entry. The apparent inconsistency is highly non-random. As this article shows, the paradoxical activities can be accounted for as specific intermediate states, leaving the rest of the activity in the consistent entries.

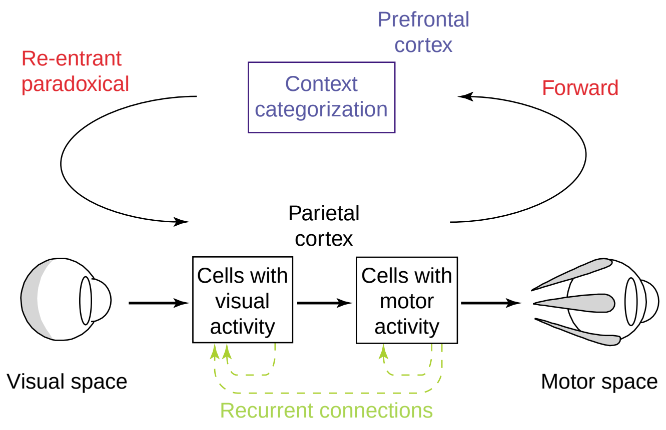

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Figure 5. Towards a solution for the context-categorization problem. Figure 1 of this article proposed a scheme for the flow of information through the brain necessary to accomplish the mixed memory-prosaccade, memory-antisaccade task. This figure maps the scheme of figure 1 onto the brain. The view focuses on parietal cortex. Parietal area LIP gets input from earlier stages of processing in visual cortex. First LIP visual neurons, and then LIP motor neurons, are activated, and the activation passes on to other brain regions, including saccadic centers such as the superior colliculus. In parallel, LIP activates other association cortical areas, probably including, the context-categorization module, which generates a switching signal fed back to LIP. The paradoxical activity is at least gated by this signal.

Implications for parietal–prefrontal inter-relationship

Parietal neurons generate paradoxical activity only after they are informed that the current trial is an antisaccade. Thus, the activity of approximately one-third of LIP visual neurons is powerfully modulated by switching signals briefly after the visual response begins. Conceivably, visual responses largely reflect the input stage to processing in LIP, and the activity of many more LIP neurons is indirectly modulated. Therefore, LIP appears logically to succeed the context-categorization module.

By contrast, prefrontal neurons with paradoxical activity show the pattern of activity expected of neurons that precede the generation of a switching signal. The neuron shown in Figure 2d appears to reflect motor intention. It seems to be active in the wrong set of trials (visual rather than motor memory-antisaccades) because this neuron precedes the context-recognition module and has no access to the output of this module, the switching signal. Because it has no access to a switching signal, this motor intention neuron does not ‘know’ that the sensorimotor transformation was replaced. It is a motor intention neuron in visual coordinates; the paradoxical activity in Figure 2d(iv) thus appears to be a motor build-up – similar to that in Figure 2b(i,ii) – but in visual coordinates.

Because approximately two-thirds of the neurons in area 46 have this paradoxical pattern of activity, this area appears largely to precede logically the output of the context-categorization module. Therefore, it is possible that the context categorization module is in area 46.

The temporal order of processing and the logical order of processing thus appear to differ from one another. The LIP precedes prefrontal cortex in the temporal order of the initial activation, consistent with the anatomical hierarchy. However, once the paradoxical activity appears in LIP (early in the trial), the logical hierarchy reverses and LIP succeeds area 46.

Hypothesis

The data outlined here lead to the hypothesis illustrated in Figure 5. It relates to the flow of information presumably necessary for context switching (Figure 1). Target onset triggers bottom-up visual processing. The primary processing stream goes through LIP visual neurons and then proceeds to other LIP neurons, including those with motor activity, and to other brain centers, including motor centers for saccadic eye movements such as the superior colliculus (SC). In parallel, a second stream transfers information to a context-categorization module, possibly in area 46. The context-categorization module generates a switching signal that is fed back into LIP. This loop is massive and rapid: the second wave of activation, which is either itself re-entrant or gated by a re-entrant switching signal, moves through LIP within only 50–100 ms after the first wave of bottom-up visual response. Until the arrival of the switching signal and the generation of the paradoxical activity, LIP precedes prefrontal cortex temporally and logically. After the arrival of the switching signal, the logical order of the two areas is reversed.

Recent evidence from Wurtz and co-workers lends tentative support to this hypothesis [14,15,49]. These investigators compared LIP projections to the frontal eye fields (FEF) and to the SC. It is recognized that FEF is a different area from area 46 and discussion of this area is beyond the general scope of this paper. However, because these data are unique, FEF will be provisionally viewed as a representative of prefrontal cortex. Projections of LIP to both SC and FEF comprise visual, sustained and motor activities. However, neurons with sustained and motor activity dominate the projection to SC; this is consistent with the hypothesis that the primary stream flows from parietal cortex to saccadic centers (‘motor space’). Neurons with visual activity dominate the projection of LIP to FEF; this is consistent with the hypothesis that the second stream flows into prefrontal cortex. Indeed, neurons with visual activity appear to dominate dorsolateral prefrontal cortex [31,50]. Access to visual information would be required to assess context from the visual input.

According to this hypothesis, the latency of the paradoxical activity reflects, at least, the latency of the bottom-up visual response, and the turn-around time of the context-categorization loop. Hence, the latency of the paradoxical activity is higher than that of the visual response. Prefrontal paradoxical activity replaces motor activity because there is a single passage through prefrontal cortex, and this passage is in visual coordinates. The parietal paradoxical activity adds to the visual activity because it reflects a second, independent wave.

Concluding remarks

The argument presented in this article could apply to domains other than the saccadic system, and could bear on the understanding of impairments to memory-saccades and to antisaccades. Such impairments are observed in neuropsychological and neuropsychiatric disorders; space restrictions preclude here a discussion of this matter. This hypothesis differs from previous ones in that it is neither strictly parietal nor strictly prefrontal but deals with the way in which these regions interact. The interaction is rapid and highly influential, consistent with the massive anatomical connections of these two regions.

If area 46 generates switching signals that act on LIP within 50 ms of the onset of LIP visual responses, why do the prefrontal neurons continue to fire long after the visual response? In the laboratory conditions of the mixed task, the sustained activity shown in Figure 2d(i,iv) seems to be redundant. In nature, context might change all the time, even just before the movement. It therefore makes sense for both the sensorimotor transformation module and the context categorization module to run continuously.

Sensorimotor transformation and context categorization modules both maintain information in working memory that is often similar. Only in conditions that influence processing in the two modules differentially does activity specific to each area emerge.

Acknowledgements

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References

1 Andersen, R.A. (1987) The role of the inferior parietal lobule in spatial perception and visual-motor integration. In *Handbook of Physiology (Section 1): The Nervous System. Higher Functions of the Brain* (Vol. 5) (Plum, F., ed.), Oxford University Press

2 Andersen, R.A. and Buneo, C.A. (2002) Intentional maps in posterior parietal cortex. *Annu. Rev. Neurosci.* 25, 189–220

3 Barash, S. *et al.* (1991) Saccade-related activity in the lateral intraparietal area. II. Spatial properties. *J. Neurophysiol.* 66, 1109–1124

4 Barash, S. *et al.* (1991) Saccade-related activity in the lateral intraparietal area. I. Temporal properties; comparison with area 7a. *J. Neurophysiol.* 66, 1095–1108

5 Bisley, J.W. and Goldberg, M.E. (2003) Neuronal activity in the lateral intraparietal area and spatial attention. *Science* 299, 81–86

6 Bracewell, R.M. *et al.* (1996) Motor intention activity in the macaque's lateral intraparietal area. II. Changes of motor plan. *J. Neurophysiol.* 76, 1457–1464

7 Chafee, M.V. and Goldman-Rakic, P.S. (1998) Matching patterns of activity in primate prefrontal area 8a and parietal area 7ip neurons during a spatial working memory task. *J. Neurophysiol.* 79, 2919–2940

8 Chafee, M.V. and Goldman-Rakic, P.S. (2000) Inactivation of parietal and prefrontal cortex reveals interdependence of neural activity during memory-guided saccades. *J. Neurophysiol.* 83, 1550–1566

9 Colby, C.L. *et al.* (1996) Visual, presaccadic, and cognitive activation of single neurons in monkey lateral intraparietal area. *J. Neurophysiol.* 76, 2841–2852

10 Colby, C.L. and Goldberg, M.E. (1999) Space and attention in parietal cortex. *Annu. Rev. Neurosci.* 22, 319–349

11 Gnadt, J.W. and Andersen, R.A. (1988) Memory related motor planning activity in posterior parietal cortex of macaque. *Exp. Brain Res.* 70, 216–220

12 Gottlieb, J. and Goldberg, M.E. (1999) Activity of neurons in the lateral intraparietal area of the monkey during an antisaccade task. *Nat. Neurosci.* 2, 906–912

13 Mazzoni, P. *et al.* (1996) Motor intention activity in the macaque's lateral intraparietal area. I. Dissociation of motor plan from sensory memory. *J. Neurophysiol.* 76, 1439–1456

14 Pare, M. and Wurtz, R.H. (1997) Monkey posterior parietal cortex neurons antidromically activated from superior colliculus. *J. Neurophysiol.* 78, 3493–3497

15 Pare, M. and Wurtz, R.H. (2001) Progression in neuronal processing for saccadic eye movements from parietal cortex area lip to superior colliculus. *J. Neurophysiol.* 85, 2545–2562

16 Platt, M.L. and Glimcher, P.W. (1997) Responses of intraparietal neurons to saccadic targets and visual distractors. *J. Neurophysiol.* 78, 1574–1589

17 Platt, M.L. and Glimcher, P.W. (1999) Neural correlates of decision variables in parietal cortex. *Nature* 400, 233–238

18 Powell, K.D. and Goldberg, M.E. (2000) Response of neurons in the

lateral intraparietal area to a distractor flashed during the delay period of a memory-guided saccade. *J. Neurophysiol.* 84, 301–310

19 Roitman, J.D. and Shadlen, M.N. (2002) Response of neurons in the lateral intraparietal area during a combined visual discrimination reaction time task. *J. Neurosci.* 22, 9475–9489

20 Sabes, P.N. *et al.* (2002) Parietal representation of object-based saccades. *J. Neurophysiol.* 88, 1815–1829

21 Shadlen, M.N. and Newsome, W.T. (1996) Motion perception: seeing and deciding. *Proc. Natl. Acad. Sci. U. S. A.* 93, 628–633

22 Shadlen, M.N. and Newsome, W.T. (2001) Neural basis of a perceptual decision in the parietal cortex (area lip) of the rhesus monkey. *J. Neurophysiol.* 86, 1916–1936

23 Snyder, L.H. *et al.* (1997) Coding of intention in the posterior parietal cortex. *Nature* 386, 167–170

24 Thier, P. and Andersen, R.A. (1998) Electrical microstimulation distinguishes distinct saccade-related areas in the posterior parietal cortex. *J. Neurophysiol.* 80, 1713–1735

25 Zhang, M. and Barash, S. (2000) Neuronal switching of sensorimotor transformations for antisaccades. *Nature* 408, 971–975

26 Boch, R.A. and Goldberg, M.E. (1989) Participation of prefrontal neurons in the preparation of visually guided eye movements in the rhesus monkey. *J. Neurophysiol.* 61, 1064–1084

27 Funahashi, S. *et al.* (1989) Mnemonic coding of visual space in the monkey's dorsolateral prefrontal cortex. *J. Neurophysiol.* 61, 331–349

28 Funahashi, S. *et al.* (1993) Dorsolateral prefrontal lesions and oculomotor delayed-response performance: evidence for mnemonic 'scotomas'. *J. Neurosci.* 13, 1479–1497

29 Friedman, H.R. and Goldman-Rakic, P.S. (1994) Coactivation of prefrontal cortex and inferior parietal cortex in working memory tasks revealed by 2DG functional mapping in the rhesus monkey. *J. Neurosci.* 14, 2775–2788

30 Williams, G.V. and Goldman-Rakic, P.S. (1995) Modulation of memory fields by dopamine D1 receptors in prefrontal cortex. *Nature* 376, 572–575

31 Constantinidis, C. *et al.* (2001) The sensory nature of mnemonic representation in the primate prefrontal cortex. *Nat. Neurosci.* 4, 311–316

32 Compte, A. *et al*. Temporally irregular mnemonic persistent activity in prefrontal neurons of monkeys during a delayed response task. *J. Neurophysiol.* (in press)

33 Fuster, J.M. (1973) Unit activity in prefrontal cortex during delayed-response performance: neuronal correlates of transient memory. *J. Neurophysiol.* 36, 61–78

34 Fuster, J.M. *et al.* (1982) Cellular discharge in the dorsolateral prefrontal cortex of the monkey in cognitive tasks. *Exp. Neurol.* 77, 679–694

35 Quintana, J. and Fuster, J.M. (1992) Mnemonic and predictive functions of cortical neurons in a memory task. *Neuroreport* 3, 721–724

36 Quintana, J. and Fuster, J.M. (1993) Spatial and temporal factors in the role of prefrontal and parietal cortex in visuomotor integration. *Cereb. Cortex* 3, 122–132

37 Fuster, J.M. (2001) The prefrontal cortex – an update: time is of the essence. *Neuron* 30, 319–333

38 Rainer, G. *et al.* (1998) Memory fields of neurons in the primate prefrontal cortex. *Proc. Natl. Acad. Sci. U. S. A.* 95, 15008–15013

39 Miller, E.K. *et al.* (1996) Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *J. Neurosci.* 16, 5154–5167

40 Assad, J.A. and Maunsell, J.H. (1995) Neuronal correlates of inferred motion in primate posterior parietal cortex. *Nature* 373, 518–521

41 Bushnell, M.C. *et al.* (1981) Behavioral enhancement of visual responses in monkey cerebral cortex. I. Modulation in posterior parietal cortex related to selective visual attention. *J. Neurophysiol.* 46, 755–772

42 Gottlieb, J.P. *et al.* (1998) The representation of visual salience in monkey parietal cortex. *Nature* 391, 481–484

43 Goldman-Rakic, P.S. (1995) Cellular basis of working memory. *Neuron* 14, 477–485

44 Mays, L.E. and Sparks, D.L. (1980) Dissociation of visual and saccade-related responses in superior colliculus neurons. *J. Neurophysiol.* 43, 207–232

45 Hikosaka, O. and Wurtz, R.H. (1983) Visual and oculomotor functions of monkey substantia nigra pars reticulata. III. Memory-contingent visual and saccade responses. *J. Neurophysiol.* 49, 1268–1284

46 Funahashi, S. *et al.* (1993) Prefrontal neuronal activity in rhesus monkeys performing a delayed anti-saccade task. *Nature* 365, 753–756

47 Edelman, G.M. (1993) *Bright Air, Brilliant Fire: On the Matter of the Mind, Basic books*

48 Schlag-Rey, M. *et al.* (1997) Antisaccade performance predicted by neuronal activity in the supplementary eye field. *Nature* 390, 398–401

49 Ferraina, S. *et al.* (2002) Comparison of cortico-cortical and cortico-collicular signals for the generation of saccadic eye movements. *J. Neurophysiol.* 87, 845–858

50 Takeda, K. and Funahashi, S. (2002) Prefrontal task-related activity representing visual cue location or saccade direction in spatial working memory tasks. *J. Neurophysiol.* 87, 567–588