Decision-Making, Behavioral Supervision and Learning: An Executive Role for the Ventral Premotor Cortex?

C. Acuña · J. L. Pardo-Vázquez · V. Leborán

Abstract In order to adjust the behavioral performance in a changing environment, subjects have to monitor their evolving actions and to know whether their responses were correct or incorrect. This requires self-awareness, cognitive flexibility, working memory (WM), and decision making that frequently are impaired in psychosis. What is the neural substrate of these processes and where are these substrates located? Dysfunction of prefrontal, parietal, temporal cortices, and associated subcortical structures are known to be involved in some of these symptoms. The prefrontal–subcortical circuits have been the main focus of study while other cortical areas such as the premotor cortex have received less attention. The main focus of this review is about the evidence that the ventral premotor cortex processes both recent sensory information and that from long-term memory to decide and evaluate the behavior of previous decisions. This process may serve for learning and thus adapting future behavior to environmental demands. Therefore, dysfunction of this cortical area could be related to some cognitive neuropsychiatric disorders.

Keywords Ventral premotor cortex · Primates · Single cell activity · Decision-making · Working memory · Outcomes

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Introduction

The conscious control of behavior is usually referred to as executive function. In psychology and neuroscience, the executive system—mainly conceived from observation of patients with frontal lobe lesions—is a theoretical cognitive system that controls and handles cognitive processes. The executive system is involved in the specification of potential actions such as planning, rule acquisition, selecting relevant information, initiating or inhibiting actions, and in the evaluation of the consequences of actions. This is important because this evaluation plays a role in learning and, therefore, in adapting to new situations in a changing environment. Decision-making is part of the executive system and consists of selecting an action from a set of available options. A decision is produced when the accrual of all evidence (e.g., sensory, contextual, past) reaches a threshold that depends on a decision rule established for that particular decision. The simplest rule is to place a criterion value that balances the decision alternatives (Gold and Shadlen 2007; Green and Swets 1966). The decision formed may produce an outcome that leads to different psychological and physiological states in the decision maker and, therefore, it is considered part of a homeostatic process (Paulus 2007). Moreover, the outcomes provoked by the decision processes can be used as a feedback mechanism to detect errors as well as correct decisions and thus actualize different components of the process (e.g., criterion, decision variable, etc.) that will be used for taking future decisions (Pardo-Vazquez et al. 2008; Quilodran et al. 2008). In fact, in order to adapt to changing social environments, adaptive decision making frequently requires re-evaluation of its outcomes and revision of the strategies used.

The executive functions are of interest to researchers of psychosis because many patients have alterations in tests of cognitive flexibility and frequently learn as fast as control subjects, but usually have problems switching strategies when the rules change. In fact, decision making can be disrupted in illnesses such as psychosis, and thus the brain areas that support these functions can be the target for new treatments (Kim et al. 2007a, b). Psychosis can take many forms and common symptoms include hallucinations, delusions, poor insight, and lack of empathy, loss of attention, and alterations in working memory (WM) and decision making (American-Psychiatric-Association 2000; Carpenter 2007; Carpenter et al. 1973; Paulus 2007). Schizophrenic patients have neuroanatomical abnormalities in the brain, including frontal, temporal, and parietal cortices, and the consensus in the field is that these abnormalities are related to the above symptoms (e.g., Amador and David 1998). Image brain studies (fMRi) have shown that schizophrenic patients compared with controls have differences in activity in frontal and parietal areas (Meyer-Lindenberg et al. 2002). Lesion of dorsolateral prefrontal (dlPFC) and orbitofrontal cortices has been associated with schizophrenia and obsessive–compulsive disorders, (e.g., Ridderinkhof et al. 2004). Disruption of prefrontal cortex (PFC), thalamus, basal ganglia, and cerebellum circuits can produce *cognitive dysmetria*, which is exemplified by difficulty in prioritizing, processing, coordinating, and responding to information, and is a characteristic deficit of altered behavior in schizophrenia and obsessive/compulsive or attention deficit disorders (Andreasen et al. 1996; Kelly and Strick 2003). An important related finding in the brain of schizophrenic patients is that of alterations in mesocortical and mesolimbic dopamine activity (Floresco et al. 2006) and it is thought that the functional balance between cortico–basal ganglia–thalamus–cortical and cerebellum–-cortico–thalamic–cortical circuits plays an important role (Drevets 2007). In fact, although antipsychotic drugs act upon more than one receptor, the main targets appear to be the dopaminergic and serotoninergic receptors. These receptors are in brain circuits that are known to be involved in WM and decision making. The frontal cortical areas that constitute these circuits are anatomically and functionally well situated to participate in the preparation and supervision of different kinds of information needed to guide behavior.

The frontal lobe is a complex structure that supports a variety of behaviors. Among other roles, it has been suggested that the frontal lobe compares the expected results with current experience to produce a smooth regulation of activity (Teuber 1964) and would be involved in prediction error, this being a mismatch between the expected and the actual outcome (Matsumoto et al. 2007; Turner et al. 2004). Also, Fuster has proposed that the frontal lobe plays a role in the temporal structuring of behavior, i.e., synthesizing cognitive and motor acts into purposeful behavioral sequences (Fuster 1997). The anatomical and functional circuits involved in the organization of behavior are beginning to be known, and it is thought that cognitive control involves the lateral prefrontal cortex and exerts its influence through top–down interactions between the lateral prefrontal cortex and premotor or posterior associative cortices (Koechlin et al. 2003). Whatever is its exact role, the frontal lobe participates in predicting and preparing behavior, a process that requires updating memories and decision making.

Working memory and decision making are the two components of the goal-directed behavior, i.e., the behavior that intends to reach an intended goal. WM and decision making are known to involve parietal, prefrontal, and premotor brain areas (Fuster and Alexander 1971; Nacher et al. 2006; Pardo-Vazquez et al. 2008; Romo et al. 2004; Shadlen and Newsome 2001). It has been proposed that two systems, represented in different brain circuits, may be operational in goal-directed behavior: vision for action and vision for perception (Lebedev and Wise 2002; Schwartz et al. 2004). In this scheme, the primary motor cortex (MI) would be involved in vision for action as its activity is not only related to planning and generating movements but also modulated by mental rotation, remembered sequences, maze solutions, or association with word meaning (Carpenter et al. 1999; Crowe et al. 2004; Georgopoulos et al. 1989; Hauk et al. 2004; Schwartz et al. 2004). The involvement of the ventral premotor cortex (PMv) in vision for perception (Lebedev and Wise 2002; Schwartz et al. 2004) is suggested by several experimental findings. The PMv receives information from sensory areas of the parietal cortex (e.g., intraparietal anterior or AIP, intraparietal ventral or VIP, intraparietal lateral or LIP) and association areas of the prefrontal cortex (dlPFC), and sends projections to the motor areas of the frontal lobe (e.g., MI and frontal eye fields or FEF) (Borra et al. 2008; Boussaoud et al. 2005; Dancause et al. 2006a, b; Ghosh and Gattera 1995; Godschalk et al. 1984; Lu et al. 1994; Luppino et al. 1999). Lesions of the premotor cortex in humans have revealed that this area is involved in apraxia, a condition in which subjects are unable to select movements and perform skilled tasks (e.g., Schluter et al. 1998). Transcranial magnetic stimulation and imaging in humans, and neurophysiologic, imaging, and lesion studies in monkeys, have suggested that the premotor cortex is involved in learning (Aizawa et al. 1991; Clower et al. 1996; Grafton et al. 1992; Halsband and Freund 1990; Lee and van Donkelaar 2006; Passingham 1989; Petrides 1986), decision making (Pardo-Vazquez et al. 2008), and evaluation of behavioral outcomes (Pardo-Vazquez et al. 2009).

In the framework of goal-directed behavior, a critical experience key for interacting with the outside and inside world is self-consciousness, the feeling, and awareness of our self, that requires awareness of one's body and one's actions. Self-consciousness is impaired in certain pathological conditions and can be due to a mismatch between perception and feeling. Poor insight is common in schizophrenia (American-Psychiatric-Association 2000), sharing an etiology with certain types of anosognosia, and is linked to dysfunction of executive functions and abnormalities in the frontal lobe (Amador and Kronengold 2004; Amador et al. 1991). Self-consciousness depends on several neural mechanisms, which include: multisensory integration in parieto-cerebellar regions and self-attribution in the PMv. For example, people with parietal lesions can show apraxia (Critchley 1953) which can reflect impaired multisensory integration of body-related information together with that of the external world (Lamotte and Acuña 1978; Mountcastle et al. 1975). A cortical ventral premotor–posterior parietal circuit can be involved in some aspects of self-consciousness that may also include the cerebellum (Ehrsson et al. 2004; Graziano et al. 1994). In fact, the PMv participates in processes that link sensory information with action as in other processes such as insight and empathy (Pardo-Vazquez et al. 2008). Connected to visual and somatosensory areas in the posterior parietal cortex and to frontal motor areas, the neurons of the PMv represent the space near the body in a body-centered reference frame (Graziano 1999; Rizzolatti and Craighero 2004). All of the above make the PMv an ideal candidate for the multisensory representation of one's own body and for the retrieval of internal information to be used in working memory, in decision making, and in learning, and for the correlation of sensory signals with actions. This is in line with the hypothesis that self-attribution—the experience that the body is part of our self—is mediated by multisensory correlations (Botvinick et al. 2004; Ehrsson et al. 2004; van den Bos and Jeannerod 2002).

Psychophysics and Neurophysiology of a Perceptual Decision

The information about the parameters of visual stimuli is represented successively in the retina, thalamus, primary visual cortex, and other areas of the brain. When the visual stimuli have disappeared, memory traces of them are left in the activity of the neurons; these memory traces can be used to encode a decision. Furthermore, internal representations kept in long-term memory (LTM) can be brought to working memory (WM) under the control of executive processes. WM refers to the active temporary storage and manipulation of information necessary to

reach a goal (Baddeley and Hitch 1974; Fuster 1995). It is divided into short-term storage and an executive process that operates on the contents of storage. The executive processes include selective attention and task management. –Experimental evidence has shown that short-term object and spatial WM components—but not the executive processes—activate the premotor cortex together with other cortical (e.g., dlPFC) and subcortical areas (Smith and Jonides 1999). These processes have been studied with behavioral tasks in which the sensory stimuli are under control and the psychophysical performance of subjects is measured and assessed. These behavioral tasks activate a large number of cortical areas each of which encodes the sensory information and combines past and present sensory information. The information about the visual stimuli used in the behavioral tasks (Nacher et al. 2006; Pardo-Vazquez et al. 2008; Vazquez et al. 2000) can reach the ventral premotor cortex from striate and extrastriate (Markowitsch et al. 1987), parietal (Borra, e al. 2008; Godschalk et al. 1984; Luppino et al. 1999), prefrontal cortices (Boussaoud et al. 2005; Lu et al. 1994), and thalamic structures (Rouiller et al. 1999; Schell and Strick 1984). The dorsal stream, which reaches the parietal cortex, is involved in sensorimotor transformations for visually guided actions whereas the ventral stream, which reaches the inferior temporal cortex, mediates information associated with perceptual identification of objects (Goodale and Milner 1992). The PMv receives information from both streams and shares the functional properties conveyed by them, as is exemplified by its role in visuomotor transformations for action and in perceptual decisions (Borra et al. 2008; Fogassi et al. 2001; Gentilucci et al. 1988; Jeannerod et al. 1995; Mountcastle et al. 1975; Murata et al. 2000; Pardo-Vazquez et al. 2008; Raos et al. 2006; Rizzolatti and Luppino 2001; Romo et al. 2004; Sakata et al. 1995).

Decision-making is a complex process that involves perceiving events or retrieving them from long-term memory, maintaining them in WM, predicting outcomes, comparing and deciding, executing an action accordingly, and evaluating the outcomes of the decision. Most decisions are made by comparing recent events with current ones, and we have studied this process with a discrimination task (CD), sketched in Fig. 1 (Vazquez et al. 2000). In this task, monkeys (Macaca mulatta) have to perceive the orientation of two lines (S1 and S2) showed sequentially and separated by a fixed delay. Then, they have to compare the orientation of S2 with the orientation of the memory trace left by S1 and decide whether S2 was oriented to the left or to the right of S1. Finally, they have to communicate the result of their decision by making an eye movement to one of the targets. If it is correct, then the monkeys are rewarded. This task allowed the investigation
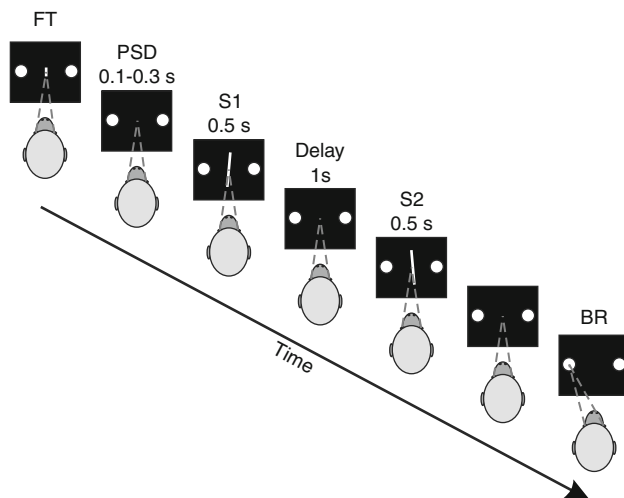
Fig. 1 Sequence of events during the discrimination task. At the beginning of the task, the fixation target (FT) and two circles appeared simultaneously in the center and at both sides of the monitor screen, respectively. The monkey initiated the trial by fixating the FT. Fixation had to be maintained during the trial; otherwise, it was aborted. When the FT disappeared and after a variable pre-stimulus delay (PSD) (100–300 ms), two stimuli (oriented lines S1, S2) each of 500-ms duration, appeared in sequence separated by a delay of 1 s. Once S2 had disappeared, the monkey made an eye movement to one of the two circles to indicate whether the orientation of S2 was to the left or to the right of S1. Correct discriminations were rewarded. S1 and S2 changed randomly from trial to trial. BR, Behavioral Response

of a wide range of processes essential to perceptual decision making (Pardo-Vazquez et al. 2008).

Although decisions can be made by comparing recent events with current ones, they are also made by comparing long-term memorized events with current ones. In this situation, the LTM-memorized stimulus is retrieved and brought to WM to be compared with the current event. If the PMv is involved in a decision process, then its neurons have to reflect the use of information from both sources. This question was addressed by recording the activity of PMv neurons while the monkeys performed in a variant of the CD task in which S1 was not shown—it was implicit—and had to be retrieved from LTM by trial and error (fixed discrimination with implicit S1 stimulus, FDIR task) (Vazquez et al. 2000).

The visual information is encoded in the activity of the ganglion cells of the retina and sent through the retino–geniculo–striate pathway to the visual primary cortex. This area encodes the orientation of the visual stimuli, which is distributed to other cortical areas (Hubel and Wiesel 1968). There is no evidence that these early visual areas either encode the visual stimuli in WM or participate in the comparison or decision processes.

The early visual areas are anatomically connected with the parietal, temporal, and frontal areas. Most probably, the information on the orientation of the visual stimuli arrives

to these areas through these connections in which the ventral and dorsal streams carry complementary information about the characteristics of the stimuli and their spatial properties, respectively (Boussaoud et al. 1990; Desimone and Ungerleider 1986; Maunsell and van Essen 1983; Pandya and Yeterian 1990; Ungerleider and Mishkin 1982; Webster et al. 1994).

The PFC and PMv encode the orientation of the visual stimuli (S1) when they are shown, and their memory traces during the delay and comparison periods. Figure 2a shows the activity of one neuron of PMv that encodes this type of information. This is a parametrical encoding; each orientation corresponds to a different neuron-firing rate (Nacher et al. 2006; Pardo-Vazquez et al. 2008). We have found that the PMv neurons also encode the orientation of S1 when it is retrieved from LTM (Fig. 2b). Therefore, the PMv neurons encode the orientation of the stimuli, both when they are presented and maintained in WM and when they have to be retrieved from LTM. This mnemonic representation is not static, but varies during the delay period; some neurons carry information about S1 during the first part of the delay, some others during the last one, and some others during the whole period (Fig. 2a–c). These facts suggest that in PFC and PMv there are neurons that carry information about S1 at different moments and that these cortical areas maintain in their activity information on the first stimulus in a dynamic way (Brody et al. 2003; Miller et al. 2003; Nacher et al. 2006; Pardo-Vazquez et al. 2008; Romo and Salinas 2003).

The high level of sustained activity of neurons during the delay period and in absence of the stimuli is interpreted as the representation of a memory trace (Fuster and Alexander 1971). During the delay and comparison periods, the firing rate of these neurons carries information about the first stimuli.

In order to reach a decision in the discrimination task, the memory trace of S1 has to be compared with the information about S2. There is no evidence that this process takes place in the early visual areas; these areas encode the stimuli during their presentation only. The comparison processes have been revealed in cortical areas up-stream to these early ones (Hernandez et al. 2002; Nacher et al. 2006; Pardo-Vazquez et al. 2008; Romo et al. 2004). If the neural activity during the comparison period is due to the interaction between the second stimulus and the trace of the first (S2–S1), then the memory trace of S1 will be present during this period, and the response to the second stimulus (S2) will signal the decision. This process was quantified with appropriate analysis (Draper and Smith 1966) that reveals the contributions of the first stimulus (S1) and the second (S2) during the comparison period. In the PFC, PMv, and medial premotor cortex (PMm), the comparison process occurs very fast. In the PMv, during
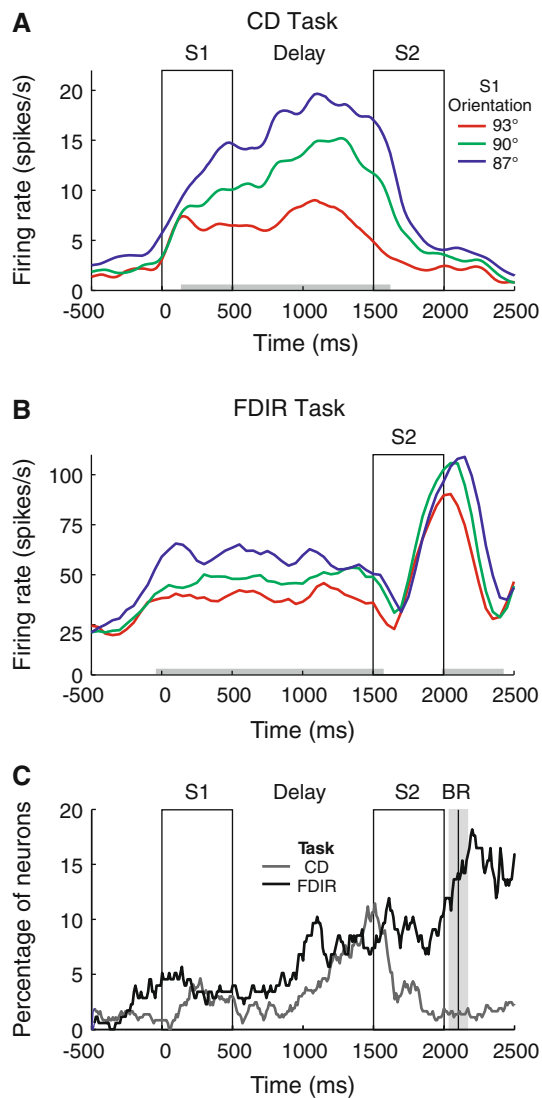
Fig. 2 PMv neurons encode the orientation of S1 both when the stimulus has been recently shown and when it has been recovered from long-term memory. The memory traces of S1 are available during the presentation of the second stimulus (S2) to perform the comparison between S2 and S1. **a**, **b**, Mean firing rates of two example neurons as a function of time and the orientation of S1 in the continuous discrimination (CD) and the fixed discrimination with implicit reference (FDIR) tasks, respectively. Gray horizontal bars signal the time periods in which the neuron significantly encodes the orientation of S1 (significance based on Step-Wise Linear Regression). **c**, Percentage of neurons that significantly encode the orientation of S1 as a function of time in the two behavioral tasks. BR, Behavioral Response ± SD

the first 40 ms of the presentation of S2, the memory trace of the first stimuli (S1) is present in the neuronal activity. Immediately, and during the following 40 ms, the trace of S1 is present together with the activity associated with S2. During the following 50 ms, the decision is represented in the firing rate. The relation between the neural activity and the monkeys' behavioral choices was studied using the

Receiver Operating Characteristic (ROC) analysis (Britten et al. 1996; Green and Swets 1966; Hernandez et al. 2002; Pardo-Vazquez et al. 2008; Romo et al. 2002, 2004), which quantifies whether the neural response to two different choices were different. The area under the ROC curve (AUC) represents the probability that an external observer, looking at the neuronal activity in a given trial, will predict the monkey's choice; values close to 0.5 indicate no difference between the two conditions, and values close to 1 indicate that the neural response is different as a function of the behavioral choice. Figure 3a shows the average firing rate of one PMv neuron as a function of the monkeys' choice. The result of the ROC analysis comparing choices "to the left" vs. choices "to the right" is shown in Fig. 3c: following the presentation of S2 (the beginning of the comparison period), the neuronal response began to separate, thereby indicating the decision that the monkey will take about 300 ms later. This pattern was confirmed at the population level (Fig. 3d), which suggests that the comparison between the stored sensory information and the current information happens in a distributed fashion (Nacher et al. 2006; Pardo-Vazquez et al. 2008).

Prediction and anticipation about future behavior is important in decision making and can rely on past experience or on environmental cues. Therefore, neurons that encode a decision could in principle predict the subject's choice. However, as the decision-related activity appears during the presentation of S2, it is also possible that neurons represent the sensory characteristics of the stimuli. The configuration of stimuli used in the discrimination tasks has allowed us to address these two possibilities by comparing trials in which the same sensory information (i.e., the same orientation of S2) led the monkeys to different choices. This represents the probability that an external observer, looking at the neuronal activity in a given trial, will predict the monkey's choice. We found that, during the presentation of S2, the response of the PMv neurons was different for different choices even when the orientation of the stimuli was the same (Fig. 3a, c, d and e). This means that neural activity is related to the behavioral choice and does not depend on the stimuli orientation.

Whether the neural activity is associated with the forming of a decision or with the planning of a motor act is an important issue because of the association of the PMv cortex with motor activity (Gentilucci et al. 1988; Godschalk et al. 1984; Matelli et al. 1986; Wise 2006; Wise et al. 1992). Comparison of trials with the same motor component but with different sensory evidence allowed us to differentiate these possibilities. This is the case of the modulation of the neural activity provoked by the difficulty of the discrimination, which is interpreted by the influence of the perceptive components of the discrimination (Gold and Shadlen 2007; Palmer et al. 2005). The difficulty of the
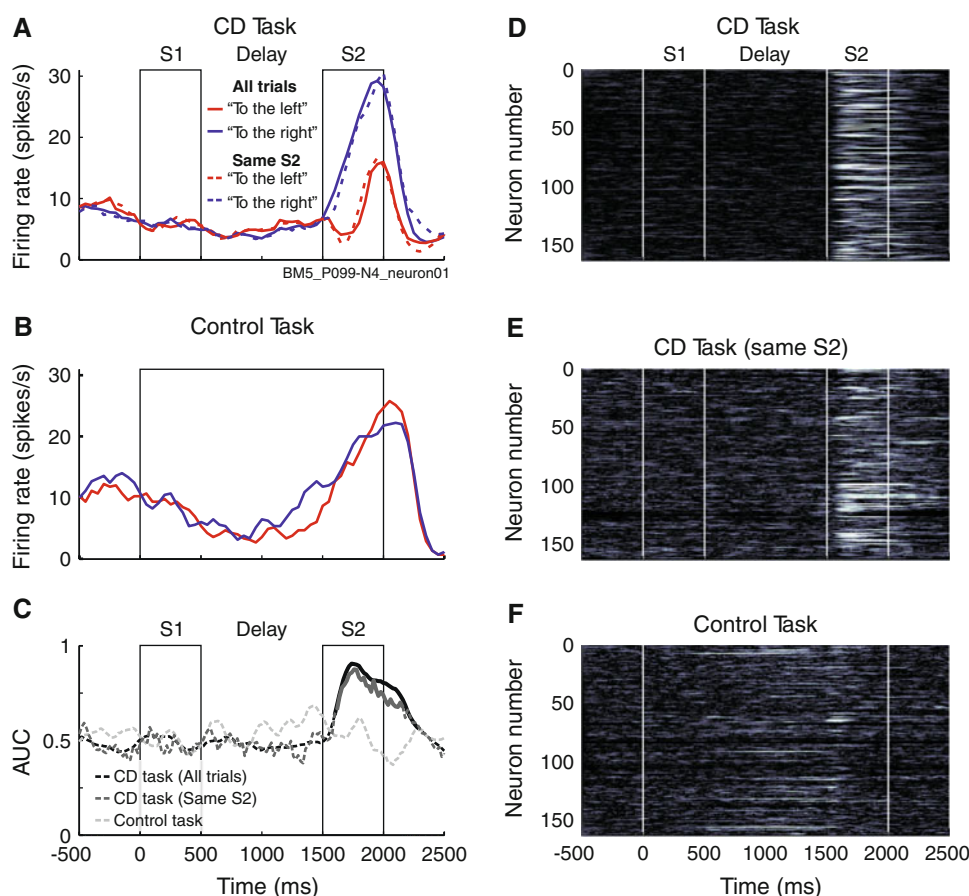
Fig. 3 The neuronal decision-related activity in PMv depends on the monkey's choice, and this activity can be explained neither by the sensory nor by the motor components of the task. **a** Mean firing rate as a function of time and behavioral choice in the CD task; continuous and dashed traces represent the average across all trials and across those trials in which the sensory information (orientation of S2) is the same but the choice is different, respectively. **b** Mean firing rate as a function of time and behavioral choice in the control task. **c** Area under the ROC curve (AUC) as a function of time and task; continuous traces represent AUC values that are significantly different from 0.5. **d**, **e**, **f** The area under the ROC curve of each neuron with decision-related activity. and with data from the two tasks are represented in each row ($N = 162$): **d** as a function of time in the CD task, **e** in the CD task selecting only those trials in which the orientation of S2 was the same, and **f** in the control task. Code from black to white indicates AUCs values between 0.5 and 1. Adapted with permission from Pardo-Vazquez et al. (2008)

decision depends on the evidence and as a consequence in the difficult trials there are more incorrect choices than in the easy ones (Fig. 4a) and the difficult decisions are taken slower than the easy ones (Fig. 4b). In the LIP, dlPFC, and PMv, the firing rate is greater for easy than for difficult decisions. The activity of the LIP neurons increases as the evidence increases and, when a certain activity level is reached, the decision is taken (Shadlen et al. 1996). This fact indicates that decisions are taken by accumulation of evidence. As a consequence, by looking at the brain activity, we can know what the result of the decision will be before its communication. In the PMv, there is an interaction between the difficulty of the comparison and the choice during the first 250 ms of the comparison period: (a) for the neuron's preferred direction, the firing rate is greater for easy than for difficult decisions; (b) for the neuron's non-preferred direction, the firing rate is greater

for difficult than for easy decisions both for single neurons (Fig. 4c, d) and for the population (Fig. 4e). Therefore, the responses are graded according to the difficulty and the direction of the decision, suggesting a correlation with the comparison process. The differences in decision-related activity between easy and difficult trials were significant, both in terms of magnitude and timing (Fig. 4f, g). This suggests that, during the first half of the comparison period, the neural activity reflects both the decision and the strength of the evidence the monkey is using to reach the decision. During the last 250 ms of the comparison period both the difficulty of the comparison and the choice modulate the neuronal response, but there is no interaction between them: the firing rate is greater for easy decisions for preferred as well as for non-preferred directions. Therefore, during the second-half of the comparison period, the neural activity can represent the likelihood of the

choice or the expected result. The comparison of the easy trials vs. the difficult trials—using the *ROC analysis*—combined with each of the choices suggests that the neuronal responses represent the strength of the evidence needed to guide the decision. As the motor component of the task is the same for easy and difficult trials, the motor component alone cannot explain the difference in decision-related activity as a function of the strength of the evidence (Pardo-Vazquez et al. 2008).

Another approach to clarify this point has been to compare the neural activity in PMv recorded in the discrimination tasks with the one in a control task, in which the motor component was the same, but no discrimination was required to reach the correct behavioral response. Most

of the neurons with choice-related activity in the CD and FDIR tasks showed no differences between the binary responses in the control task as can be seen in Fig. 3b and c for one single neuron, and in Fig. 3f for the population. These results also confirmed that the motor component of the discrimination tasks could not explain the observed differential response as a function of the decision in PMv neurons (Pardo-Vazquez et al. 2008).

Decoding the Outcomes of a Neuronal Decision

In order to adjust the behavioral performance in a changing environment subjects have to monitor their evolving
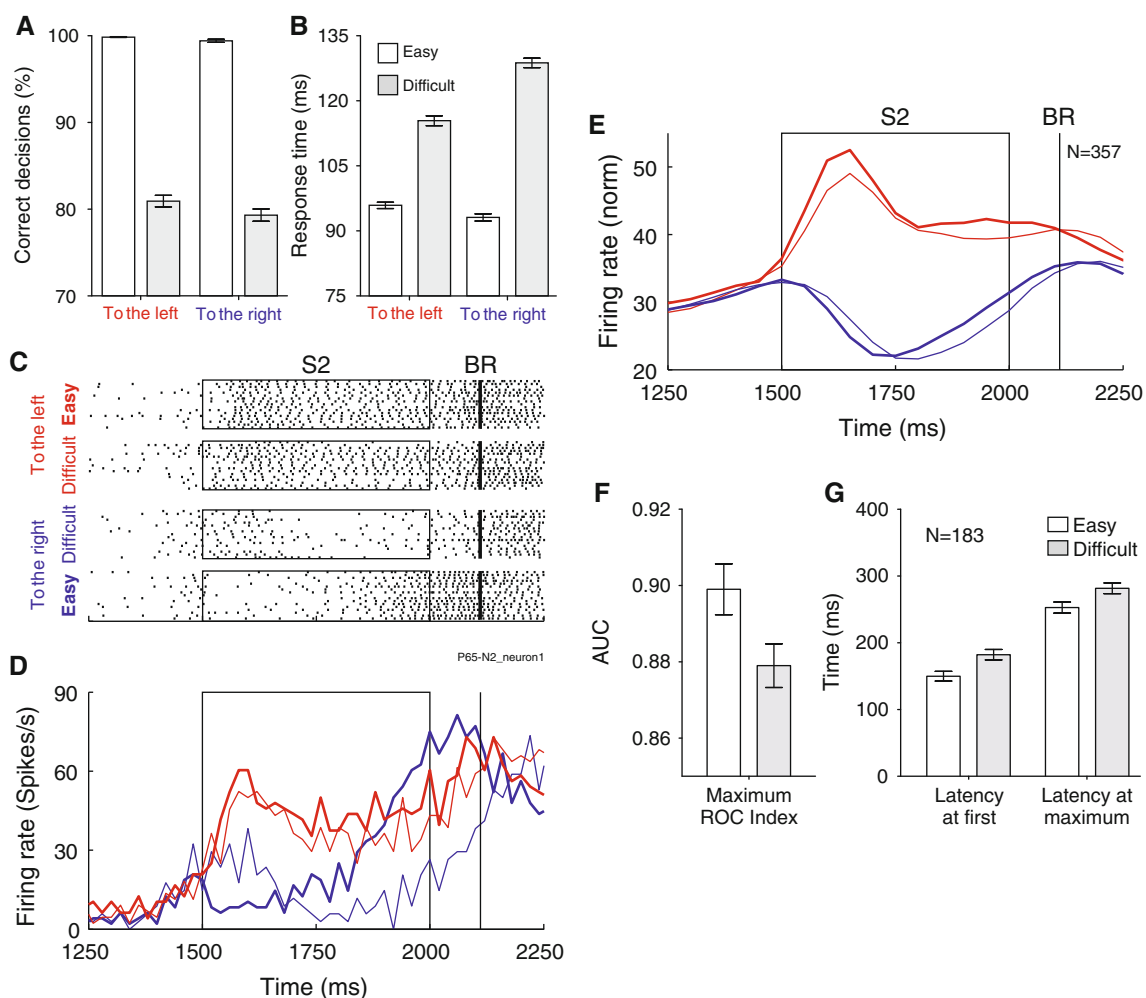
Fig. 4 The difficulty of the discrimination affects behavioral performance and is reflected in decision-related activity. **a, b** Percentage of correct decisions (mean ± SEM) and response time (mean ± SEM), respectively, as a function of the behavioral choice and the difficulty of the decisions. **c, d** Raster plot and average firing rate, respectively, as a function of time, behavioral choice and difficulty for one example neuron; BR behavioral response. **e** Firing rate, averaged across those PMv neurons with decision-related activity (*N* = 357), as a function

of time, behavioral choice and difficulty. **f, g** Maximum value of the area under the ROC curve (AUC) and latencies at first and maximum AUC values, respectively, averaged across the population of decision-related neurons with sufficient number of trials, for difficult and easy discriminations; differences in AUC and latencies were significant between easy and difficult trials (*P* < 0.01; *t* test for dependent samples). Adapted with permission from Pardo-Vazquez et al. (2008)

actions and to know whether their responses were correct or incorrect. In fact, after an error subjects slow down their behavioral response (Ridderinkhof et al. 2004; Ridderinkhof and van den Wildenberg 2005) which indicates that a neural system represents the outcome of previous trials and uses such a representation to guide future response. This information may arise from neurons in the PFC, e.g. (Watanabe 1996) and the basal ganglia e.g. (Apicella et al. 1991) which are activated by rewards gained in the course of actions. Another source of information may come from neurons sensitive to the outcomes of previous trials; the dlPFC encode past decisions and reward payoffs as well as the conjunction between these variables and may provide signals that update the animal's expectation of reward (Barraclough et al. 2004; Seo and Lee 2009). Also, outcome related activity has also been reported in the hippocampus where neurons fire at different rates after correct and incorrect responses (Wirth et al. 2009) and in the striatum, where separate groups of action- and outcome-related neurons become active only after rewarded responses are made (Lau and Glimcher 2007). Neurons in PFC and basal ganglia carry information about previous actions (Barraclough et al. 2004; Ito and Doya 2009; Kim et al. 2007a, b; Seo and Lee 2009) and both structures display simultaneous activity related to the outcomes of previous actions and have a potential causal role in subsequent task performance (Histed et al. 2009; Narayanan and Laubach 2008). These suggest that the PFC and basal ganglia might be essential brain areas for storing information about action–outcomes associations (Ito and Doya 2009; Kim et al. 2007a, b; Rudebeck et al. 2008). Another potential source of information is the medial frontal cortex (MFC), which has a role in error processing and behavioral outcomes (Luk and Wallis 2009; Ridderinkhof et al. 2004). There are neurons in MFC that preferentially respond to positive feedback and others which respond to negative feedback; moreover, the magnitude of response to positive feedback depends on the prediction error values. Thus, these responses may signal the direction and amount of error in the prediction of values of executed actions and could be related with the adjustment to subsequent choices (Matsumoto et al. 2007). The error-related negativity (Falkenstein et al. 1991) is an EEG error-related signal putatively generated by MFC and it might serve to update strategies (Frank et al. 2001; Holroyd and Coles 2002; Kerns et al. 2004). Because there is evidence that MFC and PFC are functionally related (Kerns et al. 2004; Luk and Wallis 2009), these areas may broadcast this information to other structures. Furthermore, PFC and parietal neurons become active during a dynamic decision-making task in which the animal has to discover optimal strategies and may use the outcomes as a cue (Barraclough et al. 2004; Seo et al. 2007; Seo and Lee 2009). Regarding the

influence of the encoding of outcomes in subsequent trials, it has been found that neurons in the anterior cingulate cortex (ACC) discriminate between different feedbacks depending on their behavioral relevance. This suggests a role for the ACC in triggering appropriate behavioral adaptations and suggests a role in reinforcement learning (Quilodran et al. 2008).

The PMv cortex is another area whose neurons encode the correct and the incorrect outcomes of previous behavior (Pardo-Vazquez et al. 2008). The same neurons that encoded the decision during the comparison period differentiated correct from incorrect outcomes after the monkey reported the decision. Figure 5 shows the response of two PMv neurons and the distribution of AUC values comparing correct vs. incorrect trials for the population. Some neurons fired more after correct responses than after errors (Fig. 5a, b, and c), and others have the opposite pattern of activity (Fig. 5d, e and f). The neural response for correct and incorrect outcomes suggests that the PMv is involved in performance monitoring to modulate behavioral action. A key step to integrate choices with the outcomes is the availability of a memory trace of the recently executed action. In fact, after the behavioral response, there are neurons that encode again the choices, neurons that encode the outcomes and neurons that encode the choices and outcomes together. This activity suggests that the PMv is involved in the evaluation of the consequences of the decision, and we investigated this possibility further with the implicit, FDIR task.

In order to make a decision, some everyday situations require retrieving an event from LTM. This was studied with monkeys trained to retrieve the correct orientation of S1 from LTM, compare it with a current stimulus (S2), decide whether S2 was oriented to the left or to the right and communicate the results of their decision by making an eye movement. In this scenario, the evaluation of the decision process requires the combination of three representations after the behavioral report: the orientation of S1, the choice and the outcome. The neural activity recorded in the PMv while the monkeys performed the task revealed that, after the monkeys have reported their decision, the neural activity encoded the trace of the orientation of S1 (which has been used previously) together with the decision and its outcome. Interestingly, after the behavioral response in the CD task, the trace of the orientation of the S1 used to make the choice was not encoded in the activity of these neurons. In fact, only the outcomes and the previous choice were encoded. In the CD, task S1 was shown in each trial and changed from trial to trial, thereby making its representation unnecessary. This is shown in Fig. 2c: during the last 400 ms, after the behavioral responses, the traces of S1 were represented in the FDIR but not in the CD task. The results obtained in the CD and FDIR tasks suggest that the PMv represents, after the behavioral report, all
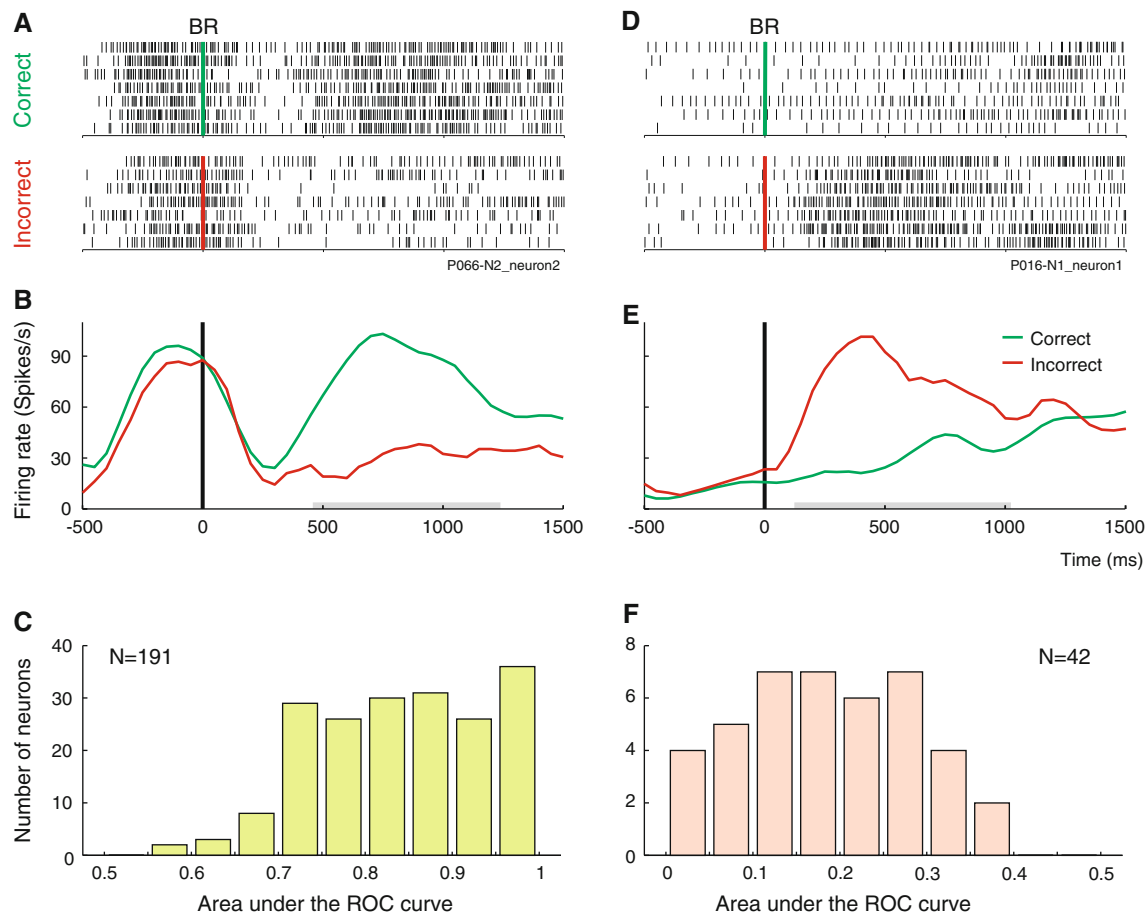
Fig. 5 The neuronal response in PMv depends on the outcome of the previous choice. Rasters (**a**, **d**) and averaged firing rates (**b**, **e**) as a function of time, sorted by correct and incorrect outcomes in the CD task, for one neuron that responded more for correct decisions and another that responded more for incorrect decisions. Gray horizontal bars signal the time periods in which the difference in firing rate is significant (based on ROC analysis); BR, Behavioral response. **c**, **f** Distributions of maximum values of the area under the ROC curve (AUC) for the population of neurons that responded more for correct and for the group of neurons that responded more for incorrect outcomes, respectively. Adapted with permission from Pardo-Vazquez et al. (2008)

the information required to evaluate the decision process, i.e., the previous choice and its outcomes in the CD task and the previous choice, its outcome, and the orientation of S1 used to make the choice in the FDIR task (Pardo-Vazquez et al. 2009).

Behavioral tasks based on value decisions or on perceptual decisions have revealed neural correlates of the outcomes of the decisions in the supplementary eye fields (SEF), PFC, ACC, PMv, and caudate nucleus (Ito et al. 2003; Lau and Glimcher 2007; Lee 2006; Matsumoto et al. 2007; Pardo-Vazquez et al. 2008, 2009; Quilodran et al. 2008; Roesch and Olson 2005; Seo et al. 2007; Stuphorn et al. 2000; Uchida et al. 2007). The representation of the outcomes after the behavioral decision is thought to be related to learning and adapting future behavior. However, except in the caudate and PFC (Histed et al. 2009), there is no empirical evidence at the present time that this is what happened in the other cortical areas in which this process has been found. The PMv has anatomical connections with the SEF, PFC, ACC, and caudate nucleus (Boussaoud et al. 2005; Dancause et al. 2006a, b; Dum and Strick 2002; Ghosh and Gattera 1995; Hoover and Strick 1993) but little is known about the hierarchical organization of the cortical and subcortical areas involved in the neural representation of errors and of correct responses of previous behavior. The PMv is considered an interface between PFC and MI (Fuster 1995) although much temporal overlap exists (de Lafuente and Romo 2006), which suggests a parallel and serial processing.

Conclusion

Subjects monitor ongoing actions and their outcomes to adjust their behavior to environmental demands. The results described here suggest that the PMv plays a key role

in processing sensory information—both current and retrieved from long-term memory—for choosing, deciding, acting, and evaluating the outcomes of previous decisions. This process may be used for adapting future behavior to environmental demands. The circuits in which the PMv is involved are complex, including cortico–cortical and cortico–subcortical ones. One functional circuit is the prefrontal lateral cortex–premotor, functionally organized as a cascade of processes mediating sensory, contextual, and episodic events. This circuit mediates the temporal organization (Fuster 1989) and the cognitive control of behavior (Koechlin et al. 2003; Shallice 1988). Another circuit includes the posterior parietal (AIP) and the premotor cortex, which is involved in visuospatial processes. Other subcortical, basal ganglia, and premotor circuits may be involved in motor and reward control (Hoover and Strick 1993, 1999). Therefore, disruption of the ventral premotor cortex could provoke decrease of insight, impairment in WM and decision making, and poor adaptation based on previous behavior, all these symptoms eing frequently observed in patients with psychosis.

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