

A role for the ventral premotor cortex beyond performance monitoring

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Depending on the circumstances, decision making requires either comparing current sensory information with that showed recently or with that recovered from long-term memory (LTM). In both cases, to learn from past decisions and adapt future ones, memories and outcomes have to be available after the report of a decision. The ventral premotor cortex (PMv) is a good candidate for integrating memory traces and outcomes because it is involved in working-memory, decision-making, and encoding the outcomes. To test this hypothesis we recorded the extracellular unit activity while monkeys performed 2 variants of a visual discrimination task. In one task, the decision was based on the comparison of the orientation of a current stimulus with that of another stimulus recently shown. In the other task, the monkeys had to compare the current orientation of the stimulus with the correct one retrieved from LTM. Here, we report that when the task required retrieval of the stimulus and its use in the following trials, the neurons continue encoding this internal representation together with the outcomes after the monkey has emitted the motor response. However, this codification did not occur when the stimulus was shown recently and updated every trial. These results suggest that the PMv activity represents the information needed to evaluate the consequences of a decision. We interpret these results as evidence that the PMv plays a role in evaluating the outcomes that can serve to learn and thus adapt future decision to environmental demands.

decision-making | outcomes | single neural activity | working memory

Decision making is a complex process essential for guiding behavior that involves evaluating past and current events and their consequences. Electrophysiological studies have shown that several cortical areas participate in the decision making process (1–15). Most decisions are made by comparing recent events with current ones. This is what happens in tasks where monkeys are trained to decide on the difference between 2 sensory stimuli (S1 and S2) showed sequentially and separated by a short interval: the continuous discrimination (CD) task (11, 16–18). This has revealed the role played by several cortical areas in decision making (4, 5, 11, 19–21), including the participation of the ventral premotor cortex (PMv) in reporting outcomes and in integrating previous choices with their consequences (12).

Decisions are also made by comparing long-term memorized events with current ones and, to our knowledge, there are few reports of the cortical areas being involved in a decision process when part of the sensory information has to be recovered from long-term memory (11). To evaluate the consequences of these decisions the information about the retrieved sensory evidence has to be available together with the information about previous choices and their outcomes. This process can be studied with the Fixed Discrimination with Implicit Reference task (FDIR), a variant of the CD task, in which S1 was implicit and monkeys had to recover its correct orientation from long-term memory (LTM) and use its internal representation in the following trials (11, 17).

We hypothesized that for the PMv to play a role in decision-making, single neurons had to combine short-term or long-term memorized sensory events with current ones. Moreover, as both the sensory information used to take the decision and the

outcomes can play a role in learning and shaping future behavior (12), we also hypothesized that this information has to be available after the behavioral response.

Here we report that in the FDIR task, PMv neurons encode the internal representation of the stimuli recovered from LTM during all task periods and use this information to reach a decision. These neurons continue encoding the memory traces together with the outcomes after the animal had made the motor report. However, these neural responses do not exist when the conditions of the task changed and the 2 stimuli were shown. We propose that the availability of memory traces and the outcomes can serve to learn and adapt future behavior to the environmental demands.

Results

We simultaneously recorded the extracellular single unit activity while 2 monkeys performed in 2 tasks. In the CD task (Fig. 1A), the monkeys had to decide whether the orientation of a current stimulus (S2) was to the right or left of a memorized trace of S1, recently shown in the visual field. Subjects perceived S1, stored a trace of it in working memory (WM) during the delay period, perceived S2, compared the orientation of S2 to the trace of S1 (S2-S1), decided on the direction of the difference in orientation between the 2 [sign(S2-S1)], and communicated the result of the decision by making an eye movement toward one target. The comparison between the orientation of S1 and S2 reflects the direction (left or right) and the magnitude of the difference (S2-S1). The direction of the difference between the 2 stimuli represents the choice [(S2-S1)]. Tasks like these have revealed that in the PMv the memorized traces of S1 were available during the delay and comparison periods so as to decide the orientation of the stimuli (5, 12).

Since that decision can be made using sensory information retrieved from LTM, we used a variant of the CD task to study this process. In the FDIR task (Fig. 1B), S1 was implicit and remained the same in a block of about 90 trials, only S2 changed. Subjects had to retrieve, at the beginning of each block, the correct S1 by trial and error. In fact, the percentage of errors diminished from the first trial (16% mean) and stabilized from the seventh trial onwards (5% mean). From then on the decision process continued as in the CD task. The most parsimonious explanation is that S1 is retrieved from LTM and maintained in WM (11, 16, 17). The behavioral results show that the monkeys' performance in the 2 tasks is close to their psychophysical thresholds and is based on the comparison of the 2 stimuli, regardless of whether they were recently shown or retrieved from LTM (Fig. S1 A and B). The study of the same PMv neurons in the 2 tasks ($n = 105$) revealed that the activity represents the monkeys' decisions regardless the orientation of S1 was shown recently in the visual world or retrieved from LTM (*SI Results*

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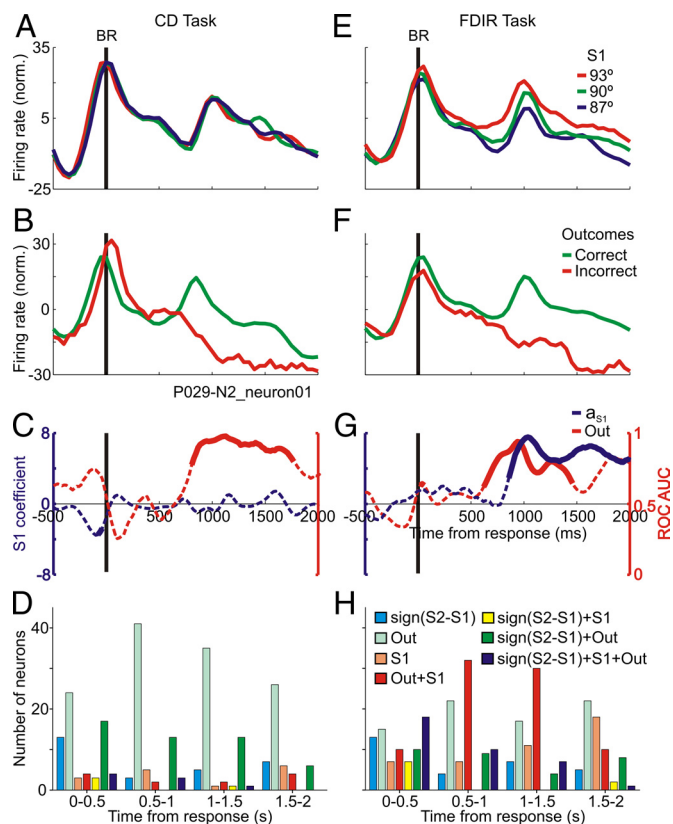


Fig. 4. After the monkey gave the BR the same neuron encoded the outcomes (Out) and the memory traces of S1 depending on the task. (A and E) Averaged firing rates sorted by S1; the memory traces are encoded in the FDIR task only. (B and F) Averaged firing rates sorted by correct and incorrect outcomes; in both tasks the same neuron differentiated correct from incorrect trials. (C and G) ROC AUC for correct vs. incorrect trials and SLR a_{S1} coefficient, as a function of time; continuous traces indicate significant values. (D and H) Number of neurons that carried significant information (ROC and SLR analysis) about the components of the decision in CD and FDIR task. Time intervals taken from the behavioral response. The same neurons can be represented in more than one time period.

after the behavioral report would not have that behavioral meaning because S1 is presented in every trial and subjects do not need to predict which S1 will appear in the following trial and this interpretation is consistent with our results.

Comparison with Other Studies. Our observation that PMv neurons reflect the decision process and the correct and incorrect outcomes suggest that they are associated with reporting the decision and encoding the sensory signals on which the decision is based. Some of our findings in PMv agreed with those reported by Romo et al. (5) with a vibrotactile CD task. They identified neurons involved in the decision process which were driven by vibrotactile stimuli and their traces during the delay and com-

parison periods. Similar results were described in other cortical areas (4, 5, 11, 18, 21). In the medial premotor cortex, when the decision report was postponed, the neural activity between the end of the stimuli and the motor report reflected again the monkey's choice and the sensory information (18). In our task, we have investigated what happened after the monkeys emitted the motor report, finding that when needed (FDIR task) the neural activity reflected concurrently the outcomes, the memory traces of the stimuli and the choices used to take the decision.

The adaptation of the PMv neural activity to the demands of a perceptual task suggests that this cortical area may use past and current information for assessing the result of the decision and if it is necessary adjust the behavior in the next one.

Materials and Methods

Discrimination Tasks. Monkeys were trained to perform in 3 tasks, already described in detail: continuous discrimination, control task (12, 17), and fixed discrimination with implicit reference (FDIR, (11, 17)) (SI Methods). Here we report on the same neurons studied in the CD and FDIR ($n = 105$) (Fig. 1). All these neurons were task-related (Wilcoxon test, $P < 0.01$). Some of them could be also studied in a motor control task ($n = 59$; SI Methods). Animals (BM5, 8 kg and BM6, 6 kg) were handled according to the standards of the European Union (86/609/EU, Spain (RD 1201/2005) and the Society for Neuroscience Policies and Use of Animals and Humans in Neuroscience Research. The experimental procedures were approved by the Bioethics Commission of the University of Santiago de Compostela.

Recordings. Neuronal recordings were obtained with tungsten microelectrodes (1.5–3.5 M Ω) in the posterior bank of the ventral arm of the *sulcus arcuatus* and adjacent surface in the Premotor ventral cortex in the 4 hemispheres of the 2 monkeys (Fig. 1D). The locations of the penetrations were confirmed through standard histological techniques for the 2 recorded monkeys. Recordings sites changed from session to session.

Data Analysis. All analyses were performed using custom-made programs in Matlab R2008b with Exlink Toolbox. We considered a neuron's response as task-related if during any of the task periods (PSD, S1, delay, S2, behavioral response, and until 2,000 ms after the behavioral response) the firing rate—averaged across each period—was significantly different from the control period preceding the white noise on at the beginning of each trial (Wilcoxon test, $P < 0.01$). Neural activity dependences were obtained through Receiving Operating Characteristics (ROC) (37) and Stepwise Linear Regression (SLR) analyses (12, 38). The ROC analysis allows the measure of the degree of overlap between 2 response distributions (13, 21, 39). For each neuron with sufficient data (at least 5 trials for each condition) we computed the area under the ROC curve (ROCAUC) within a time bin of 100 ms that was slid in 20 ms steps until the entire periods of the task had been analyzed. Detailed information is in SI Methods.

Stepwise Linear Regression analysis (SLR) was used to establish the dependence between the firing rate and (a) S1, (b) S2-S1, (c) the choice (sign(S2-S1)) (5, 12, 21, 38). The resulting a_{S1} , a_{S2-S1} and $a_{\text{sign}(S2-S1)}$ coefficients were plotted as a time function. The dynamics of those coefficients were calculated using a sliding window of 100 ms moving in 20 ms steps throughout the neuron-firing rate. Coefficients were included in the model if P value for a predictor was lower than 0.02 for at least 2 consecutive bins. The deviation from the mean ($2SD$) was used to determine the significant time periods for each coefficient. Detailed information is in SI Methods.

Behavioral analyses have already been described (11, 12) (Fig. S1).

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