Simultaneous Encoding of Multiple Potential Reach Directions in Dorsal Premotor Cortex

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Cisek, Paul and John F. Kalaska. Simultaneous encoding of multiple potential reach directions in dorsal premotor cortex. J Neurophysiol 87: 1149–1154, 2002; 10.1152/jn.00443.2001. We present evidence that the primate brain can simultaneously generate discrete directional signals related to multiple alternative reaching actions before making a decision between them. A monkey performed a task in which the correct target for a reaching movement was specified during two consecutive instructed-delay periods. First, two potential targets were presented; and second, a nonspatial cue identified one of them as the correct movement target. During the first period, two directional signals coexisted in the activity of cells in dorsal premotor cortex (PMd), oriented toward the two potential targets. During the second period, one of these disappeared and the remaining signal predicted the monkey’s response choice. These results suggest that, when faced with multiple salient opportunities for reaching, the primate brain performs sensorimotor transformations in parallel to begin planning several reaching movements simultaneously before selecting one for overt execution.

INTRODUCTION

Information from the external world continuously presents us with multiple conflicting opportunities for action. Psychological theories commonly assume that the brain acts on this information by first internally representing the external world, formulating judgments and deciding on a course of action, and then preparing and executing the chosen motor plan (Johnson-Laird 1988; Marr 1982; Miller et al. 1960; Shafir and Tversky 1995). In the context of this perspective, it is often assumed that movement-related cortical regions represent only a single plan for reaching movements, which is generated after decision-making is complete.

However, a growing number of behavioral studies challenge the assumption that the motor system prepares itself for the performance of only a single action at a time. For example, the presence of a distractor has been shown to influence the reach trajectory to a target (Tipper et al. 1998, 2000; Welsh et al. 1999) and hand grasp aperture (Castiello 1999). Patients with frontal lobe damage often cannot suppress actions associated with distractors even while they are planning actions directed elsewhere (Humphreys and Riddoch 2000). It has been proposed that such effects are the result of competition among parallel simultaneous representations of potential actions (see Castiello 1999 for review). These proposals suggest that when multiple graspable objects are within reach, the nervous system can begin preparing, in parallel, multiple potential reaching movements, which should appear as distinct directional signals in reach-related regions (Tipper et al. 2000).

A number of studies provide evidence that cells in premotor and primary motor cortex are activated by partial information about ensuing movement choices before one is selected (Bastian et al. 1998; Kurata 1993; Riehle and Requin 1989), but it is not clear whether this activity reflects a generalized nonspecific activation or specific signals related to distinct response options. The possibility of simultaneous encoding of multiple movements is also supported by observations that these regions are involved in representing memorized sequences (Carpenter et al. 1999; Kettner et al. 1996; Mushiake et al. 1991), but determining whether this representation consists of co-existing distinct directional signals is made difficult by serial order effects on neural activity in such tasks. More fundamentally, it is not yet known whether the presentation of two equally probable but mutually exclusive reach targets, only one of which will eventually serve as the goal of an overt arm movement, engages the motor system to generate directional signals related to both options, as predicted on the basis of behavioral studies. Our preliminary data from the dorsal premotor cortex of a rhesus monkey suggest that movement planning begins as soon as information specifying likely options is available, even in situations where preparation could in principle be delayed until after all information relevant for decision-making was provided. Some of these results have previously appeared in abstract form (Cisek and Kalaska 1999).

METHODS

Behavioral tasks

A monkey (Macaca mulatta) performed a variant of a center-out reaching task using a manipulandum moving in the horizontal plane. Gaze was unconstrained, and eye movements were measured at 100 Hz using an infrared oculometer (Dr. Bouis, Karlsruhe).

In the two-target task (Fig. 1A), the monkey began each trial by placing the on-screen cursor within a central green circle (1.5-cm radius) for a 500-ms center-hold-time. Next, two colored cue circles (2-cm radius), one red and one blue, appeared at two of eight possible target locations on the circumference of an 8-cm radius circle, for a spatial-cue-on period (1,000 ms) and then disappeared for a spatial-
<p>cue-off period (0–1,500 ms). Here, we only present data from trials in which the targets were opposite to each other. Next, the central circle changed color to either red or blue, for a color-cue period (1,500–2,500 ms). This change in color instructed which of the two memorized color-coded spatial-cue locations was the selected target for the upcoming movement. Finally, the central circle disappeared, and eight identical green circles (2-cm radius) appeared at the eight peripheral locations. This go signal instructed the monkey to move to the selected target. Trials were presented in a randomized-block sequence balanced for all pairs of opposite location-color combinations, color choices, and selected target locations. If the monkey made an error, the trial was shuffled back into the remaining trial sequence, and not immediately repeated (see Crammond and Kalaska 2000).

Two control tasks were also performed. In the one-target task (Fig. 1B), the stimulus sequence was the same, but only one cue appeared during the spatial-cue period, whose color always matched the central color during the color-cue period. Thus a single potential movement was specified with full certainty from the onset of the spatial-cue period, and the color cue provided no new behaviorally relevant information. In the delayed-match-to-sample (DMS) task, the stimuli were the same as in the two-target task, but their order of presentation was reversed, the color-cue period preceding the spatial-cue. Thus in the DMS task the color cue was completely uninformative on its own about movement directionality, but was behaviorally relevant and had to be memorized so that the correct response could be selected after the presentation of the two subsequent spatial-cue targets.

Cortical recording

Recording chambers were implanted surgically under inhalation anesthetic, and conventional techniques were used to isolate and record single-unit activity from the cerebral cortex. All procedures followed university and national guidelines for animal care.

Data analysis

Cells were examined if they exhibited task-related changes of activity during either the one- or two-target task and showed directional preferences in at least one task epoch. Each cell’s mean discharge rate (including partial spike intervals) was calculated for each epoch of each trial. A cell’s baseline was computed as the average activity during center-hold-time. For each cell, a directional tuning function was calculated for each epoch by averaging the activity across all trials with a selected target at each of the eight directions, pooling trials with red and blue selected targets together. The preferred direction (PD) of each cell in each epoch was calculated using trigonometric moments. Tuning functions were first tested for unimodal directional tuning by a nonparametric bootstrap test (Georgopoulos et al. 1988) with 1,000 repetitions and a criterion of $P < 0.01$. If a tuning function was not found to have significant unimodal directional tuning, it was then tested for bimodal tuning (Batschelet 1981).

To investigate the possibility that multiple simultaneous directional signals are present in the PMd population, a population vector analysis (Georgopoulos et al. 1983) is not suitable because it collapses the distribution of directional signals into a single vector pointing in the direction of the weighted average. Instead, population activity during each epoch was characterized by computing a plot of the global “directional-bias” as follows: the circle was divided into 36 10° wedges, and each cell was assigned to the wedge into which its PD fell, as determined during the corresponding epoch in the one-target task. The length of each wedge was determined by summing the change in activity above baseline of all of the cells in that wedge and dividing by the number of those cells. A separate set of 36 wedges was computed for each of the 8 possible selected target locations, and all 8 of these were pooled together after rotating them such that the selected target location was oriented to the right. Thus each cell contributed activity to eight of the wedges. The result represents the mean distribution of directional activity in the population averaged over movements to all eight targets. This distribution was then tested for a unimodal bias using a bootstrap test (1,000 repetitions, $P < 0.01$). If it failed the test for a unimodal bias, it was tested for a bimodal bias. This analysis was performed both with and without normalization of each cell’s contribution by its maximum discharge rate, but since the results were qualitatively similar, we report here only the results without normalization.

RESULTS

We report here the activity recorded from 150 task-related neurons in the arm region of dorsal premotor cortex (PMd) from two hemispheres of one monkey. The majority of the cells (97%) could be classified into one of three types on the basis of the task epochs during which their activity was sig-
nificantly directionally tuned according to the bootstrap test for unimodal or bimodal tuning. This classification is not meant to imply the existence of strictly distinct cell types, but rather to delineate regions along a continuum of cell properties.

Twenty-six movement (M) cells (17%) were not directionally tuned during the spatial-cue and color-cue periods in either task, and became unimodally tuned only after the go signal appeared, with similar PDs in both tasks (not shown). Nine arm muscles for which percutaneous electromyographic (EMG) records in both tasks were obtained also behaved this way.

Forty-eight selected-response (SR) cells (32%) showed significant directional tuning before the go signal but only after the monkey had unambiguous information on the target for movement (Fig. 2A). In the one-target task, 28/48 (58%) of these cells became unimodally tuned during the spatial-cue period, while the remaining 20 cells did not meet the bootstrap criterion for unimodal tuning until the color-cue period. In the two-target task, all of these cells were untuned during the spatial-cue period and became unimodally tuned during the color-cue period, with a PD similar to that during the one-target task.

Seventy-two potential-response (PR) cells (48%) became directionally tuned shortly after spatial-cue targets were presented in either task (Fig. 2B). In the one-target task, they were unimodally tuned during the spatial-cue period. During the spatial-cue period of the two-target task, these cells were active whenever one of the potential targets appeared near their PD. As a result, when trials were sorted by the ultimately selected target, the tuning curve of a PR cell during the spatial-cue period of the two-target task was statistically bimodal (bootstrap test, \( P < 0.01 \)). This bimodal tuning function does not imply that a PR cell signals movements in two opposing directions. Rather, a PR cell signals the presence of a potential target in its PD, and the bimodal tuning function is a consequence of plotting activity with respect to the final target for movement. For 43/72 (60%) PR cells, the bimodal pattern was sustained during the spatial-cue-off period, after the targets themselves had disappeared (see the spatial-cue-off tuning curve for the cell in Fig. 2B, dotted line). During the color-cue period of the two-target task, PR cells sustained or further increased their activity if the central color specified movement toward the target near their PD. If the central color indicated the opposite target, the cell activity typically decreased abruptly. Thus PR cells exhibited a unimodal tuning curve during the color-cue period of the two-target task, with a PD similar to that in the one-target task (Fig. 2B). The term “potential-response” implies that these cells are more involved in planning responses than in representing stimuli. Arguments in favor of this interpretation follow here and in the DISCUSSION.

These three cell types were not distributed uniformly across the region of cortex studied. M cells were most common caudally, whereas PR cells became more common rostrally. SR cells were found more uniformly throughout the region. Thus the information contained in the activity recorded from the most rostral part of PMd studied differs from the information recorded from more caudal regions. Several of the more caudal penetrations lie in primary motor cortex (Fig. 1C), although the
precise reconstruction of the locations of recorded cells is not complete.

We divided the cell population into two separate groups lying either caudal or rostral to a line aligned with the genu of the arcuate sulcus (see Fig. 1C), and pooled the data across cells in each group to generate population directional-bias plots. As shown in Fig. 3A, in the one-target task both populations were unimodally tuned (bootstrap test, $P < 0.01$) during both the spatial-cue and the color-cue periods. In the two-target task (Fig. 3B), the caudal population was untuned (did not meet the significance criterion for either unimodal or bimodal tuning) while both options were still possible, and became unimodally tuned ($P < 0.01$) only after the nonspatial color cue indicated the correct target. In contrast, the rostral population generated a bimodal pattern ($P < 0.01$) of directionally tuned activity during the spatial-cue period of the two-target task, whose two peaks were oriented toward the two potential targets. This bimodal pattern confirmed that the rostral cell population retained information related to two specific response choices rather than simply exhibiting a nonspecific generalized activation during the period of uncertainty. Once the nonspatial color cue specified the selected target, the component of the population directional-bias pattern oriented toward the rejected target disappeared, and the population generated an unambiguous unimodal signal pointing in the direction of the monkey’s choice. The contrast between rostral and caudal cell properties appears more abrupt at the population level (Fig. 3B) than at the single-cell level, since PR cells also made up 23% of the caudal population.

In 12% of trials in the two-target task, the monkey moved to the wrong target. The discharge of PR and SR cells during the color-cue period reliably predicted the monkey’s behavioral choice, during both correct and error trials, irrespective of the conjunction of sensory cues that preceded the movement (Fig. 3, B and D).

Ten PR cells and four SR cells were studied in the DMS task. During the initial color-cue period, no significant main effect of direction or color was found for any of the cells (2-way ANOVA, $P < 0.01$). When the two spatial-cue targets subsequently appeared, most of the cells showed significant main effects of target direction, and 7/10 PR cells were unimodally tuned (bootstrap test, $P < 0.01$) even though two targets were continuously visible (of the remaining cells, 1 was bimodally tuned and 2 were untuned). Figure 3C shows the directional-bias for these 10 PR and 4 SR cells recorded during the DMS task, confirming that this population was unimodally tuned ($P < 0.01$) during the spatial-cue period. These preliminary results demonstrate that the presentation of two targets is of itself not sufficient to evoke a “sensory” response to their choice.
appearance if the monkey has prior information to select one as the target for a reach.

**DISCUSSION**

The main finding of the present study is that, in the two-target task, the appearance of two salient visual instructions on opposite sides of a central starting location simultaneously activated two distinct subpopulations of rostral PMd cells (PR cells) with opposing directional preferences. This generated a bi-directionally tuned pattern of population activity whose bimodal directional bias reflected the spatial relationship between the two signals and/or their associated motor responses (Fig. 3B). When a subsequent nonspatial signal provided the remaining information necessary to select the final target, one of the activated subpopulations ceased to respond or was actively suppressed, while the discharge of the other continued or was enhanced, and a further subpopulation of PMd cells (SR cells) was recruited into activity thereby reinforcing the unidirectional signal after the final choice was made.

The bimodal directional-bias observed in the rostral population (Fig. 3B) may be interpreted in a number of ways. First, it may simply reflect a sensory response to the appearance of the two spatial-cue stimuli, or a short-term working memory of these stimuli (since 60% of PR cells maintained their bimodal tuning after the targets disappeared). If that were the case, then a bimodal directional-bias should also be observed during the spatial-cue period of the DMS task, when identical stimuli are presented. However, the presentation of the two targets in the DMS task elicited a unimodal response over the duration of the spatial-cue period, despite the continued presence of the rejected target (Fig. 3C). Furthermore, the unimodal tuning of both PR and SR cells during the color-cue period of the two-target task (evoked by the nonspatial color cue) was similar to their tuning during the entire delay period of the one-target task (evoked by a spatial cue). Thus, although these cell responses are evoked by salient sensory events, they are much more strongly related to the information provided by these sensory events about the directionality of the potential movements than to the physical properties of the stimuli themselves. Many previous studies specifically designed to evaluate whether cell responses in premotor regions are more sensory or motor in nature have argued against an interpretation of PMd activity as simple sensory responses (Boussaoud and Wise 1993a,b; Boussaoud et al. 1996; Crandall and Kalaska 1994, 2000; di Pellegrino and Wise 1993a,b; Kalaska and Crandall 1995; Mitz et al. 1991; Vaadia et al. 1986).

Alternatively, the bimodal activity pattern of PR cells may be generated by overt oculomotor behavior or covert shifts of attention (Boussaoud et al. 1996). However, the bimodal discharge pattern was often sustained during the spatial-cue-off period, even though the monkey typically fixated the central target during that period (Cisek and Kalaska 2000), awaiting the color cue. The bimodal activity at that time could not be generated by gaze shifts. The same observation argues against the proposal that the bimodal pattern is caused by covert shifts of attention, which are generally coupled to overt gaze shifts when no constraints are placed on oculomotor behavior (Kowler et al. 1995; Lebedev and Wise 2001).

Finally, the bimodal activity pattern of PR cells may be a correlate of information specifying, at some level of abstraction, two potential directions for movement. In all conditions studied, the activity of a PR cell can be parsimoniously described as follows: a potential-response cell discharges when the animal is instructed that a movement toward the cell’s preferred direction is a potential action that will result in reward, even when other potential actions are available. Thus multiple options for movement co-exist in the population of PR cells as signals reflecting the relative directionality of the potential movements in our task. A further observation supporting this interpretation is that the color-cue-period activity reliably predicted the movement the monkey ultimately made during both correct and error trials in the two-target task (Fig. 3D), irrespective of the conjunction of sensory cues that preceded the movement.

The suggestion that the primate brain can begin to specify simultaneously the direction of several alternative reaching movements, before making a decision between them, is similar to observations made in the oculomotor system, where activity evoked by multiple potential targets has been reported (Basso and Wurtz 1998; Kim and Shadlen 2000; Munoz and Wurtz 1995; Platt and Glimcher 1997; Schall and Thompson 1999). Together with these studies of the oculomotor system and behavioral studies of reaching movements (Castiello 1999; Tipper et al. 1998, 2000; Welsh et al. 1999), the results presented here support a theoretical framework that contrasts with the traditional description of behavior as a passive analysis of the sensory world followed by deliberation and then preparation of a chosen motor response (Johnson-Laird 1988). They suggest that behavior should instead be viewed as a continuous competition among early representations of multiple potential actions, expressed in various degrees of elaboration, reflecting currently available opportunities for interaction with the environment.

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**REFERENCES**


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