Supplementary Material

Medial Frontal Cortex Motivates but does not Control Movement Initiation in the Countermanding task

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Voluntary control of behavior implies the ability to select what action is performed. The supplementary and pre-supplementary motor areas (SMA, pre-SMA) are widely considered to be of central importance for this ability, due to their role in movement initiation and inhibition. To test this hypothesis, we recorded from neurons in SMA and pre-SMA of monkeys performing an arm countermanding task. In our main paper, we describe three main findings. First, we found that the majority of movement-related neurons in SMA and pre-SMA carried signals that were neither sufficient nor necessary for the control of arm movement initiation. Second, a minority of neurons contained activity sufficient to play a role in inhibiting movement. Third, the activity of many neurons was dependent on the expectation of reward, and modulated by the size of the reward. Here we discuss a number of additional issues regarding our findings and alternative interpretation than the ones we suggest in the main text.

S1. Localization of recorded neurons

We used the branch of the arcuate sulcus as an anatomical landmark for the border between pre-SMA and SMA. This landmark does not always coincide perfectly with the border. Nevertheless, it seems clear that we recorded from both pre-SMA and SMA, based on the known location of these two areas with respect to the arcuate sulcus (Luppino et al., 1991; Matelli et al., 1991; Matsuzaka et al., 1992; Luppino et al., 1993; Liu et al., 2002). The two populations show some differences, such as the earlier onset times of pre-SMA neurons relative to SMA neurons (Figure 9). However, with respect to the countermanding analysis, which is the central topic of this paper, the movement-related neurons have strikingly similar characteristics across both pre-SMA and SMA. Thus, our main finding holds true for both areas.
S2. Alternative interpretations of the movement-related activity in the countermanding task

We interpret our finding in the countermanding task as evidence that pre-SMA and SMA do not carry signals sufficient to control movement initiation. However, it has been suggested that pre-SMA and SMA are specialized in the control of self-generated movements, in contrast to movements triggered by external cues which are controlled by premotor cortex (Eccles, 1982; Goldberg, 1985). Thus, it might be presumed that the countermanding task does not allow an adequate test of the role of pre-SMA and SMA in the initiation of self-generated movements. This conclusion, however, seems unlikely, since multiple recording studies have shown that both SMA and the pre-motor cortex contain neurons that are active only during self-generated movements, or only during externally cued movements, as well as neurons that are active during both types of movements (Okano and Tanji, 1987; Romo and Schultz, 1987; Kurata and Wise, 1988; Thaler et al., 1988).

In this study, we tested neuronal activity using only two horizontal target positions. In a recent paper, Russo and co-workers measured the directional tuning of SMA neurons during visually guided two-dimensional movements (Russo et al., 2002). They report that most neurons show a broad tuning width (median: ~120 deg). This result fits with our findings that most neurons were directionally tuned, but the tuning was so broad that they were active in both directions. We assume that the SMA neurons encode movement-relevant information using a population code. The contribution or weight of each neuron to this distributed representation would be proportional to the strength of its activity (Georgopoulos et al., 1982; Lee et al., 1988). In this case, movement-related neurons should also carry signals sufficient to control movement initiation for directions away from the optimal target location, as long as they show significant activation. Thus, it is unlikely that our negative finding results from the fact that some movement-related neurons in our sample were not tested using optimal target locations.

S3. Final decision whether or not to act

The final decision as to whether or not a planned movement is carried out must be made downstream of pre-SMA or SMA. One possibility is that it takes place in the primary motor cortex (M1). A recent countermanding study in humans found that in M1, corticomotor excitability was reduced and intracortical inhibition was significantly greater on Stop trials
compared with No stop signal trials at a time that preceded the onset of muscle activity (Coxon et al., 2006). These results indicate that inhibitory networks within M1 might contribute to volitional inhibition of prepared action. Another possible location for the final decision could be the basal ganglia (Mink, 1996). The internal segment of the globus pallidus (GPi) inhibits thalamic and cortical neurons, and thus serves as a block on the initiation of any action. The direct pathway through the striatum releases an action by inhibiting a specific set of GPi neurons. Both the hyperdirect pathway through the subthalamic nucleus (STN) and the indirect pathway from the striatum through the external segment of the globus pallidus suppress actions by more wide-spread excitation of GPi (Mink, 1996; Nambu, 2004). A recent human neuroimaging study provided evidence for a role of the STN and the hyperdirect pathway in countermanding (Aron and Poldrack, 2006).

**S4. Alternative interpretations of the reward contingent movement activity**

Movements that were accompanied by high activity were immediately followed by reward, but there were also other differences in the movements. The interpretation of pre-SMA and SMA activity as a motivation signal is therefore not the only possible explanation of our data. One alternative interpretation is that systematic differences in the mechanics of the arm movements itself might explain the neuronal activity differences. The EMG activity was more influenced by the direction of the movement than by whether or not the movement was rewarded. Nevertheless, there were clear differences in the EMG activity strength during center-out and return movements. For a variety of reasons we do not think that this difference in muscle activity could explain the difference in neuronal activity of the reward contingent cells. First, the preceding countermanding analysis shows a clear disassociation between the neuronal and muscle activity. The majority of the movement-related neurons are strongly activated during Canceled trials, when the muscles are much less active or not active at all. If neurons reduce their activity they do so after the muscles. Thus, it seems unlikely that the neurons we recorded from directly reflect differences in muscle activity. Second, the reward-contingent movement cells are characterized by a complete absence of activity during return movements. In contrast, the EMG activity difference is much more moderate. We computed two reward modulation indices to describe both pre-SMA/SMA neurons and muscles. There are clear differences in the distribution of these indices between neurons and muscles (Figure 15). If we were to assume
that such a large difference in the neural activity results from the moderate activity difference in muscle activity, we would have to conclude that the majority of neurons (pre-SMA: 86%; SMA: 66%; total: 75%) are only recruited during time periods of high muscle activity. Such an assumption does not seem to fit previous reports about the relationship between SMA activity and EMG activity levels (Crutcher and Alexander, 1990; Padoa-Schioppa et al., 2002), or our finding that these same neurons are strongly activated when the muscles are less active than normal. Third, during correction and return movements the EMG activity was almost identical. Thus, at least for the neurons that were active for correction but not return movements, it does not seem plausible that the neuronal activity differences (Figure 13C) are the result of differences in muscle activity (Figure 14C).

A more likely alternative interpretation of the neuronal activity is that it could reflect some other cognitive difference between the movements. One possibility is the presence or absence of a movement goal indicated by the visual cue. The return movement was made during the inter-trial interval, when the center box was not present. However, previous experiments have shown that most SMA neurons were similarly active during self-initiated movements (such as the return movement) and movements guided by sensory cues (such as the movements towards the target) (Okano and Tanji, 1987; Romo and Schultz, 1987; Kurata and Wise, 1988; Thaler et al., 1988). Thus, we do think that the presence of a visual target alone is unlikely to be a major source of the activity modulation. Another possibility is the behavioral contexts of the various movements, which have different degrees of complexity. The movement to the target is generated in the presence of a competing incentive to wait a little while longer for the possible occurrence of a stop signal, while the return movement is generated without any competing motor plan. However, the correction movements are likewise free of competition and possible conflict. Therefore, conflict as such cannot explain the activity of pre-SMA and SMA neurons during these trials. More experiments are necessary to distinguish between different possible hypotheses about the contribution of pre-SMA and SMA to motor control.

S5. Reward contingent movement activity as a signal of motivational drive

Roesch and Olsen have studied how reward size affects activity across many brain regions, including the rostral part of the SMA and the premotor cortex (Roesch and Olson, 2003, 2005). They found that activity was modulated by the size of reward and the proximity of
response to reward, and found this was particularly evident for regions closer to the primary motor cortex. They describe the observed changes in activity as representing value dependent motivational modulations of motor preparation signals. Our findings are consistent with these reports. When we altered the countermanding paradigm to include high and low reward conditions, we observed activity modulated by the size of expected reward in both the pre-SMA and SMA. However, our task revealed an additional aspect of the signals. The activity during the movement period was contingent on the expectation of reward. If this activity simply represented a modulated motor signal, we would expect to see activity also on return movements, but with a smaller magnitude of response. Rather, it appears that the reward-dependent activity we observe is representing a motivational signal, which modulates the motor activity and is absent during actions that are not instrumental in obtaining reward, and therefore have no or only very small incentive value.

References:


