A relative position code for saccades in dorsal premotor cortex

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Supplementary Material

Estimation bias in the statistical test for separability

The idealized neuronal responses in **Fig 2** show that separability is associated with a first singular value whose amplitude is large compared with the second singular value. It is difficult to establish statistical significance by directly comparing the amplitude of the first and second singular values as they are ordered amplitudes with the first singular value being necessarily larger than the second. To avoid this problem, we defined separability by a significantly ($p < 0.05$) large first singular value compared to the first singular value calculated when trial conditions were randomized by permuting the rows and columns of the response matrix (Randomization test, 10,000 permutations). Unlike permuting the trial labels and then recalculating the response matrix, permuting the rows and columns preserves the variability of the response matrix.

To test whether the above procedure for testing for separability is subject to estimation bias, we simulated the idealized neuronal responses for the six cases presented in Fig 2 as we varied the amount of data available for estimation. We generated 3, 5, 10, 100, 1000 or 10000 simulated trials for each configuration by drawing the number of spikes in each trial from a Poisson distribution with a mean rate corresponding to the value of the response matrix. The means were scaled so that the maximum firing rate in the response matrix was 50 Hz. We then calculated the separability probability in each case. **Fig S1** presents the results. We found that even shallow gain fields were reliably classified as separable ($p < 0.05$). This occurred with as

few as three trials per condition and did not drastically change as the number of trials per condition increased to 10000. In addition, the simulated vector response and both of the simulated intermediate responses were classified as inseparable (p > 0.05). Therefore, the procedure we used for determining separability is not subject to appreciable estimation bias and can reliably detect gain fields with as few as three trials per condition.

Comparing PMd saccade responses with PRR saccade responses

PRR neurons responded less before saccades than PMd neurons. Across the population of 140 PRR neurons, we found 102 PRR cells were spatially tuned to either reaches or saccades. This population included 90 cells (90/140; 64%, p<0.05) that were spatially tuned to reaches and 60 PRR cells (60/140; 43%, p<0.05) that were spatially tuned to saccades, albeit weakly at times. As proportions of the 102 spatially tuned PRR cells, 42 cells (42/102; 41%) were exclusively tuned to reaches and not saccades, 12 cells (12/102; 12%) were exclusively tuned to saccades not reaches, and 48 cells (48/102; 47%) were tuned to both reaches and saccades (see Table 1; Main text). The 48 PRR neurons (25 in Monkey E; 23 in Monkey Z) tuned to both reaches and saccades also had similar preferred directions for reaches and saccades with a mean difference of 6° (**Fig S2**). PRR neurons had a unimodal distribution of overall preferred directions that was peaked in the visual hemifield contralateral to the recording site (Rayleigh test, p<0.01).

Our finding of strong a lateralization of the preferred directions of PRR neurons differs from earlier work studying the reach tuning of parietal neurons that shows a more uniform tiling of the workspace (Lacquaniti et al., 1995). The difference in results may be due to two factors. First, we recorded from PRR in the bank of the intraparietal

sulcus, while earlier work has recorded from more superficial cortical regions on the gyrus of Brodmann's Area 5. Activity in the bank of the sulcus in the superior parietal lobule is more visual in nature than activity on the surface (Colby and Duhamel, 1991; Buneo and Andersen, 2006) and appears to be similar to area LIP on the lateral bank of the intraparietal sulcus, an area that shows strong lateralization of activity before saccades (Quian Quiroga et al., 2006), Second, we made our recordings under enforced fixation while earlier recordings from Area 5 were done during free-gaze. The activity of parietal neurons is centered on the orientation of gaze (Batista et al., 1999; Buneo et al., 2002; Pesaran et al., 2006), and changes in eye position during freely-made eye movements has been shown to affect the responses of parietal neurons that are active before reaches (Cisek and Kalaska, 2002).

Comparing the spatial reference frame for saccades and reaches

In a previous study (Pesaran et al., 2006), we recorded from PMd and PRR neurons while monkeys performed a reach relative position coding task (**Fig S3**). This task was identical to the saccade relative position coding task in the present study, with the exception that it required a reach instead of a saccade. Before reaches, we had previously found that individual PMd neurons were spatially tuned to multiple vectors, T_G, H_G and T_H, We had also found that the strength of spatial tuning to these vectors was equal (Pesaran et al., 2006). **Figure S4** presents the reach data for comparison with the saccade data presented in the main text (**Fig 10**). The number of PMd cells with tuned, inseparable responses to T_G, T_H and H_G before reaches and their intersections are shown in a Venn diagram (**Fig S4A**). Cells tended to encode a mixture of tuning to more than one vector and many encoded all three vectors. This pattern was mirrored in the strength of tuning to each vector. Examining the tuning strength of the response matrices using the length of the resultant of the gradient analysis revealed that

before reaches, PMd neurons encode all three vectors, T_G, T_H and H_G, with equal strength (**Fig S4B**). These data stand in contrast to the responses of PMd cells during the saccade relative position coding task (**Fig 10**), in which cells were more likely to encode only one of the vectors, and tended to code the vector H_G the strongest, followed by T_H and then T_G. Thus the spatial encoding scheme for saccades and reaches are mostly similar in PMd, albeit with some differences.

Tuning to hand and gaze position during baseline

The strength of relative hand-gaze encoding suggests PMd neurons may also encode the position of the hand and/or gaze in the absence of a plan to move. This signal could maintain postural information which could then be combined with incoming target information to plan movements. To investigate this representation, we analyzed how activity during the baseline period of the task before target presentation depended on the static position of the hand and gaze. Using the matrix analysis, we found that the activity of many PMd cells was tuned to hand and gaze position during the baseline before a saccade (53/116; 46%; $p<0.05$ randomization test).   A similar fraction of PMd cells was tuned to hand and gaze position during the baseline before a reach (51/111; 46%; $p<0.05$) and these two proportions were not significantly different ($p=0.70$; Two-sample binomial test). The resultant of the gradient analysis showed that the strength of tuning of baseline activity in each task was also not significantly different (Reach baseline tuning strength: $p=0.87$; Rank-sum test). This shows that baseline tuning to gaze and hand position is widespread in PMd neurons and is not influenced by whether a saccade or reach movement will follow.

Baseline response matrices of PMd neurons showed diagonal more than horizontal or vertical structure. HG position response matrices for individual cells peaked when either the hand was ipsilateral to the eye (**Fig S5A**), as well as when the hand was

on the eye, or the hand was contralateral to the eye. For the population of PMd cells tuned during the baseline period, baseline tuning for hand position could not be separated from gaze position for a majority of cells (**Fig S5B**. 43/53; 82%) inseparable; p>0.05, bootstrap test). We found that inseparable PMd cells encoded the difference between hand and gaze position with a mean response field orientation -86° (**Fig S5C**).

These analyses indicate that the activity of PMd neurons is affected by moving the hand to the left as much as by moving gaze to the right, and vice versa. Interestingly, the level of activity at the peak of the response field was greater when the hand was ipsilateral to gaze than when the hand was contralateral to gaze (p<0.05, Rank-sum test). This means cells in PMd prefer the hand ipsilateral to gaze. We observed the same relative hand-gaze position preference in both the reach and saccade relative position coding tasks. Cells which preferred the hand ipsilateral to gaze in the reach task, tended to also prefer the hand ipsilateral to gaze in saccade task (**Fig S6**). This configuration of hand and eye position is more common during behavior and is consistent with reports of a preference for gaze centered with respect to the body (Scherberger et al., 2003). Therefore, preferred relative hand-gaze position of individual neurons in PMd may match the statistics of natural behavior.

References

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Figure Captions

Figure S1 Assessment of estimation bias in the procedure for calculating separability. The probability of separability is plotted as the number of trials per condition from three to 1000 trials for each of the six idealized neuronal responses shown in **Fig 2**. Intermediate I presents results for the response shown in **Fig 2B**. Intermediate II presents results for the response shown in **Fig 2C**. For display purposes, we added 10^{-4} to the medium gain field results and 2×10^{-4} to the shallow gain field results. Dotted line shows p=0.05 level used for establishing significance.

Figure S2 Population histogram of difference in preferred directions during delay periods before saccades and reaches for PRR neurons. Asterisk marks the mean preferred direction difference. Preferred directions before a reach and saccade point in similar directions.

Figure S3 Reach relative position coding task. A reach is made from one of four initial hand positions on a line to one of four target positions while gaze is maintained at one of four gaze positions. Hand positions and reach targets are shown in green, gaze positions are shown in red.

Figure S4 PMd delay period responses during the reach relative position coding task. **(a)** Venn diagram of the number of neurons with tuned inseparable TG, HG and TH responses during the reach relative position coding task. **(b)** Tuning strength of the reach response matrices. * denotes significant difference (p<0.05).

Figure S5 Hand and gaze (HG) tuning during the baseline period of the saccade relative position coding task. **(a)** Example PMd neuron response. The PMd example cell from **Figure 7** (main text) is shown. Numbers denote average firing rate for each hand-gaze combination. **(b)** Population HG separability for PMd neurons. **(c)** Population HG response field orientation for PMd neurons. Orientations for separable cells are shown in dark grey. Orientations for inseparable cells are shown in light grey. Similar responses were seen during the baseline period of the reach

Figure S6 Relative hand-eye position preference during the baseline period for neurons recorded in both reach and saccade reference frame tasks. The number of neurons with a preference for the hand ipsilateral to the eye, aligned with the eye or contralateral to the eye is shown for each task.
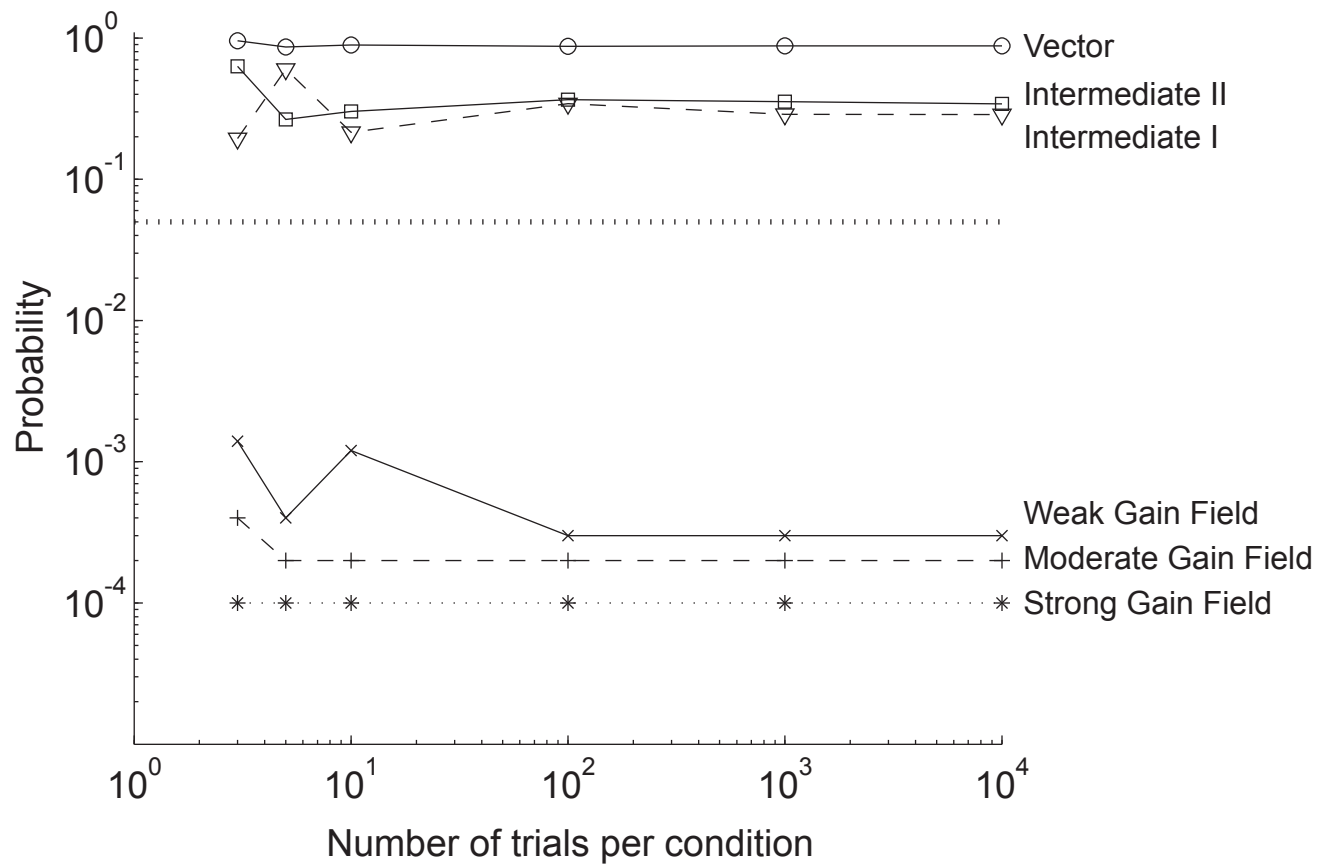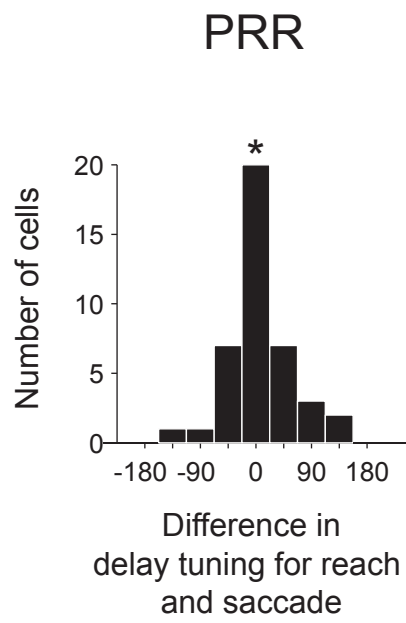
Figure S1

Figure S2

PRR

Difference in
delay tuning for reach
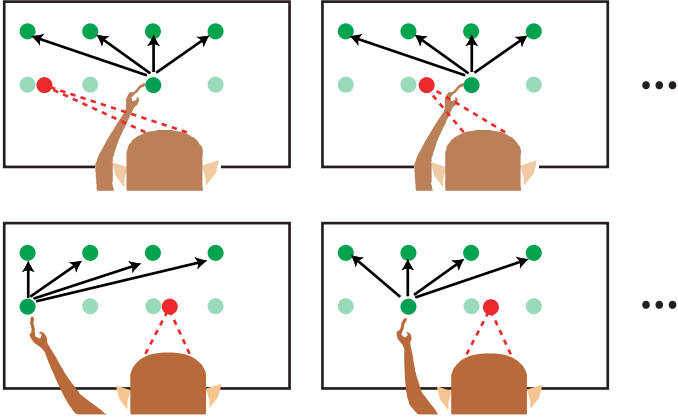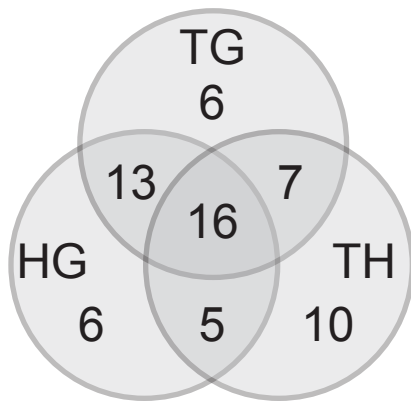and saccade

Figure S3

Reach relative position coding task

Figure S4

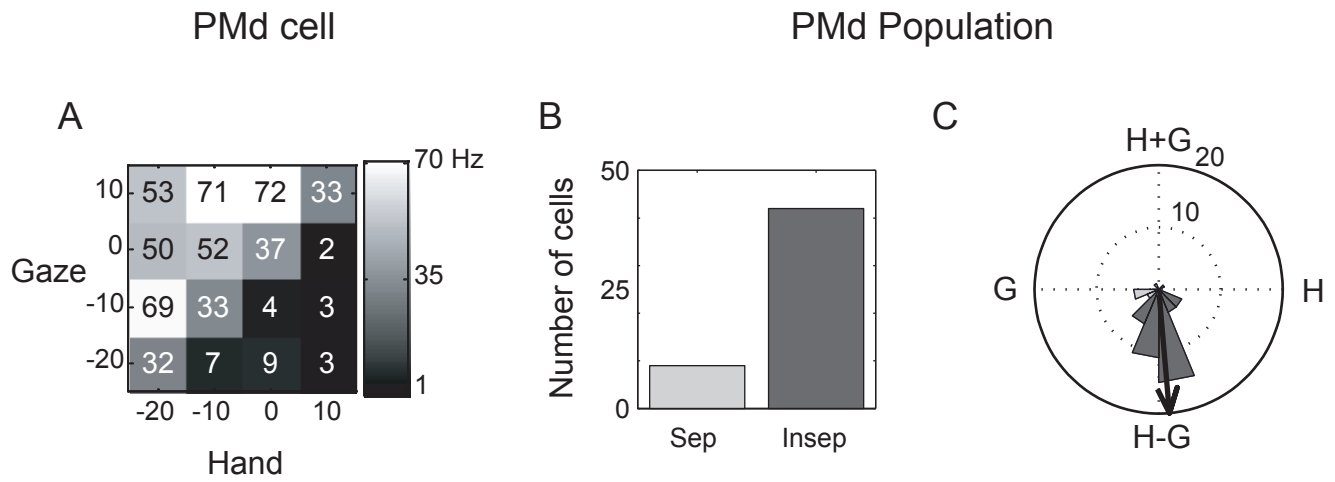## Reach Relative Position Coding

A

B

Figure S5

PMd cell

A

PMd Population

B

C

Figure S6

Saccade Task

HIE

	HCE	HIE	
HIE	4	3	9 cells
	5	2	5
HCE	3	1	1

HCE

HCE   HIE

Reach Task

HIE: Hand ipsi to eye

HCE: Hand contra to eye