SUPPLEMENTARY MATERIAL

Planning Ahead: Object-Directed Sequential Actions Decoded from Human Frontoparietal and Occipitotemporal Networks

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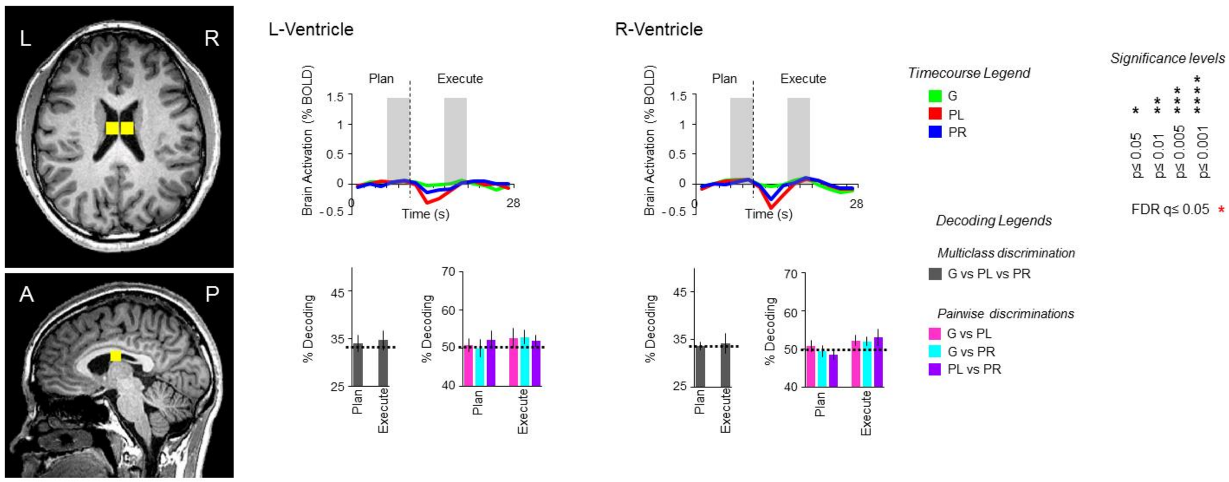

Figure S1: Decoding in the non-brain control ROIs. Non-brain control ROIs were defined in each subject (denoted in yellow; example subject shown). Percentage signal change time courses, decoding accuracies and confusion matrices are plotted and computed the same as in Fig. 5. Note that no significant differences were found during either the Plan or Execute epoch with two-tailed t-tests across participants with respect to chance classification levels. When combined with the 'in-brain' control analyses performed in SSc, these findings suggest that successful action decoding throughout several of the frontoparietal and occipitotemporal areas truly reflects an encoding of intended object-directed movement sequences. L = left; R = right; A = anterior; P = posterior. G = Grasp-to-Hold, L = Grasp-to-Place-Left, R = Grasp-to-Place-Right.

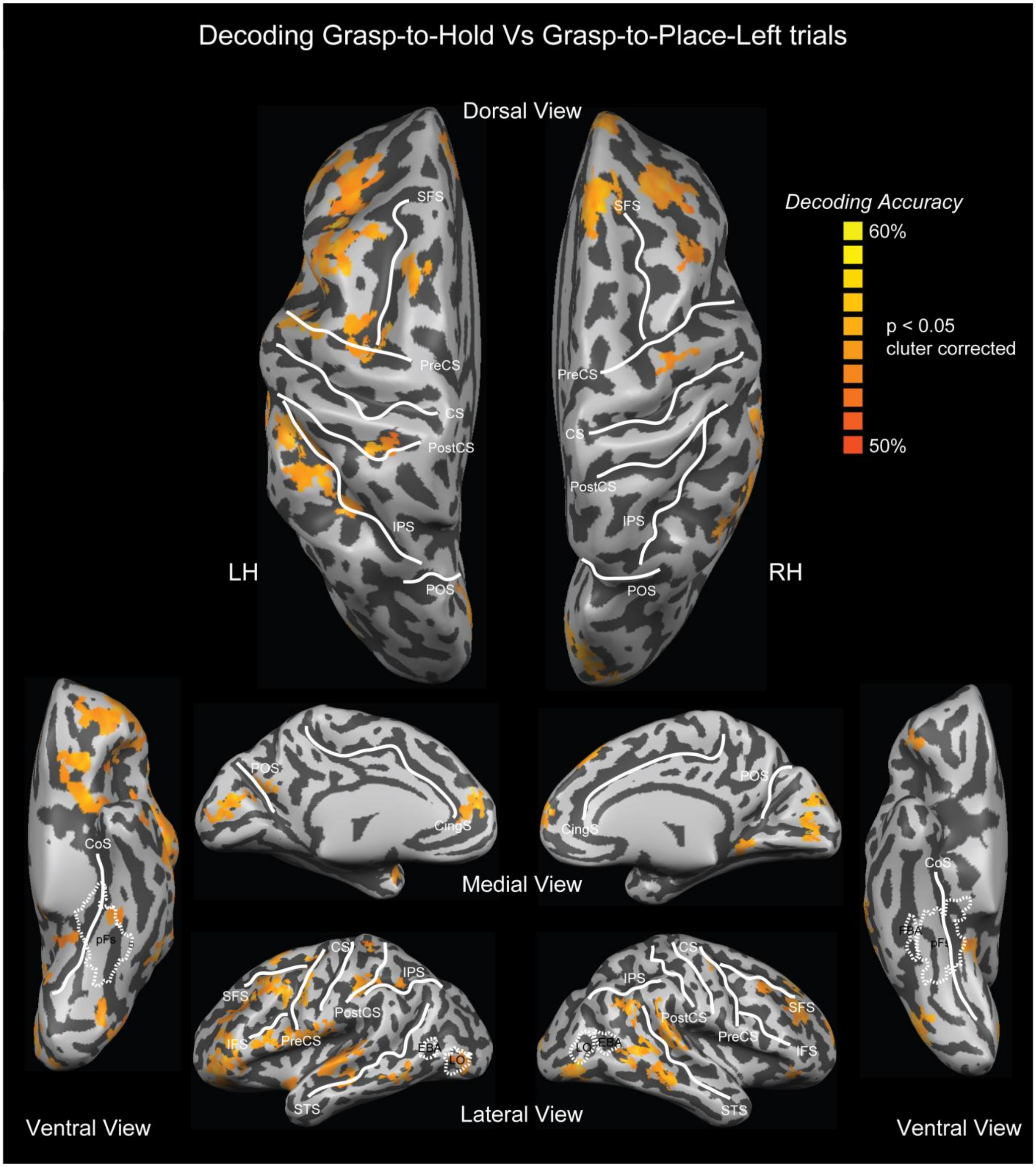

Figure S2: Results of whole-brain searchlight analysis for the decoding of Grasp-to-Hold vs. Grasp-to-Place-Left trials during the Plan epoch. Group-averaged (N = 14) classification maps shown on the inflated, Talairach-normalized left and right hemispheres of one representative participant. Occipitotemporal brain areas, identified at the group-level using the functional localizers (Random effects analysis, $p < 0.005$, cluster corrected), are outlined in dashed white lines and labelled in black text. Major sulci are denoted by solid white lines and labelled in white text. All classification results are statistically thresholded at $p < 0.05$ (cluster corrected). See Fig. 2 caption for sulci acronyms.

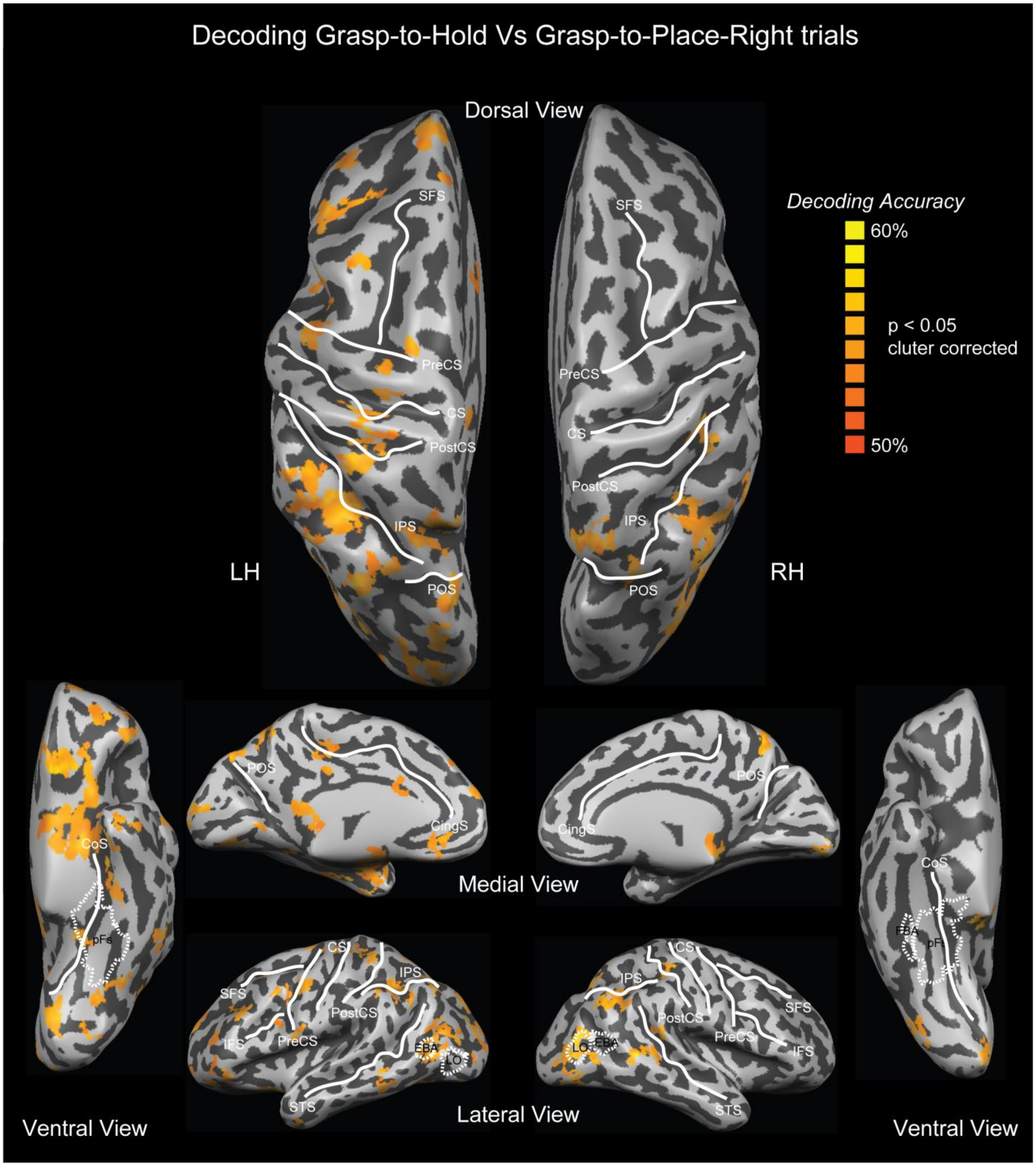

Figure S3: Results of whole-brain searchlight analysis for the decoding of Grasp-to-Hold vs. Grasp-to-Place-Right trials during the Plan epoch. Results are shown and computed the same as in Fig. S2.

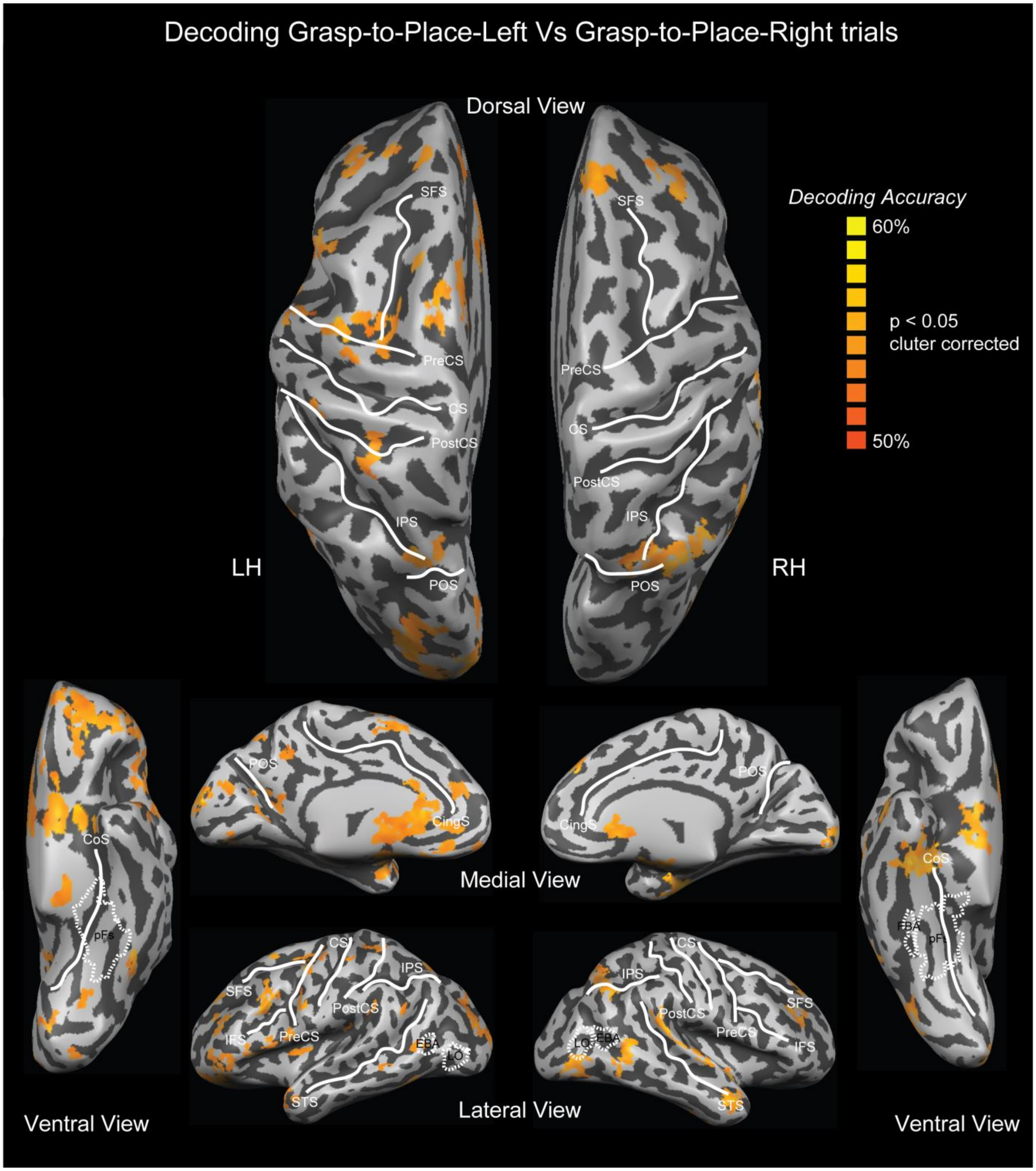

Figure S4: Results of whole-brain searchlight analysis for the decoding of Grasp-to-Place-Left vs. Grasp-to-Place-Right trials during the Plan epoch. Results are shown and computed the same as in Fig. S2.

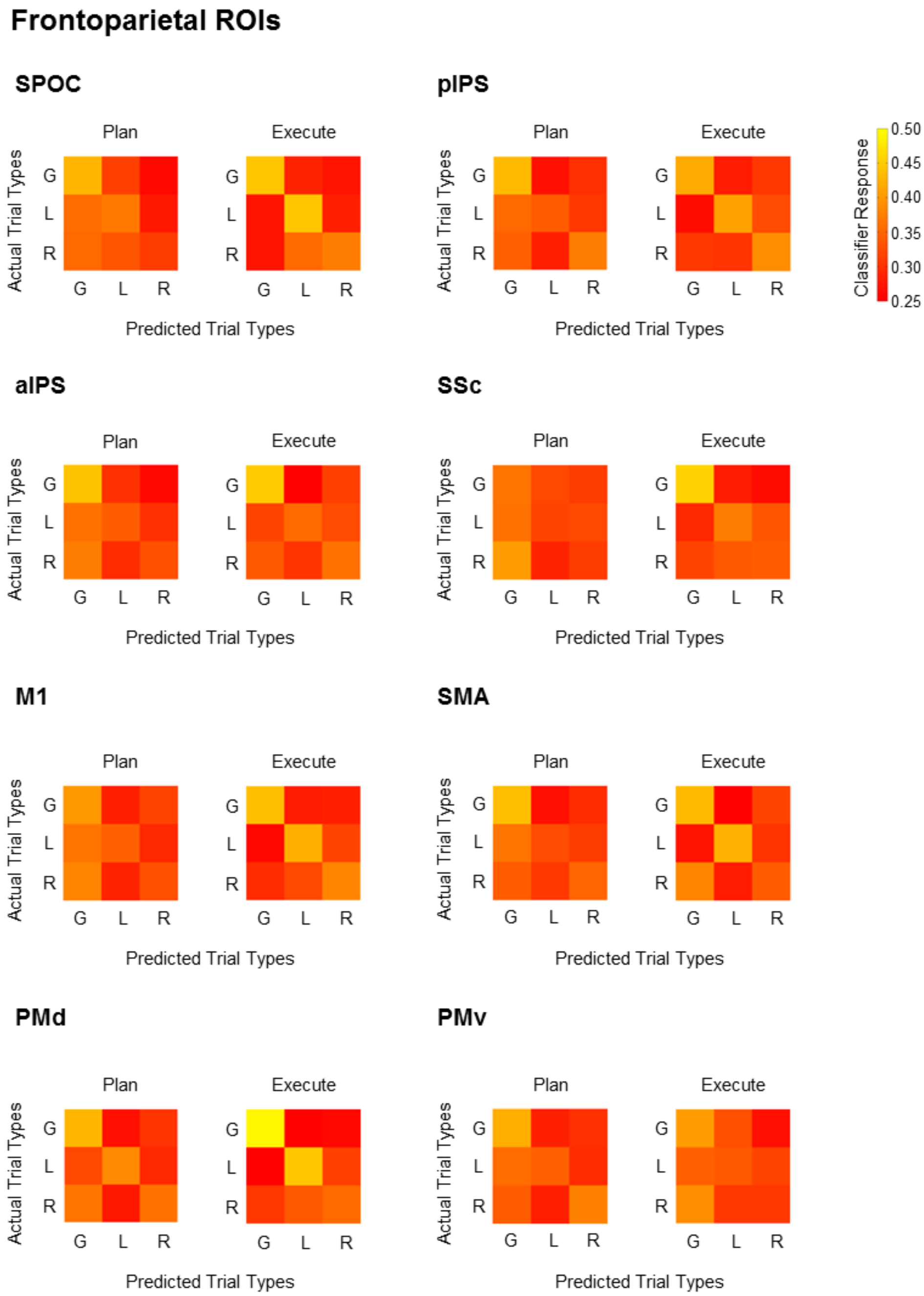

Figure S5: Confusion matrices generated from the multiclass discriminations in frontoparietal cortex. The average classifier response proportions across participants are shown. When decoding is perfect, the confusion matrix will have a diagonal containing values of 1 and the rest of the matrix will be 0. Note that the average decoding performance (shown in gray bars, Figs. 5-6) is defined as the mean across the diagonal. To highlight differences in decoder performance, the matrices have been scaled between 0.25 and 0.5 (rather than being scaled from 0-1). For further details, see Materials and Methods. G = Grasp-to-Hold, L = Grasp-to-Place-Left, R = Grasp-to-Place-Right.

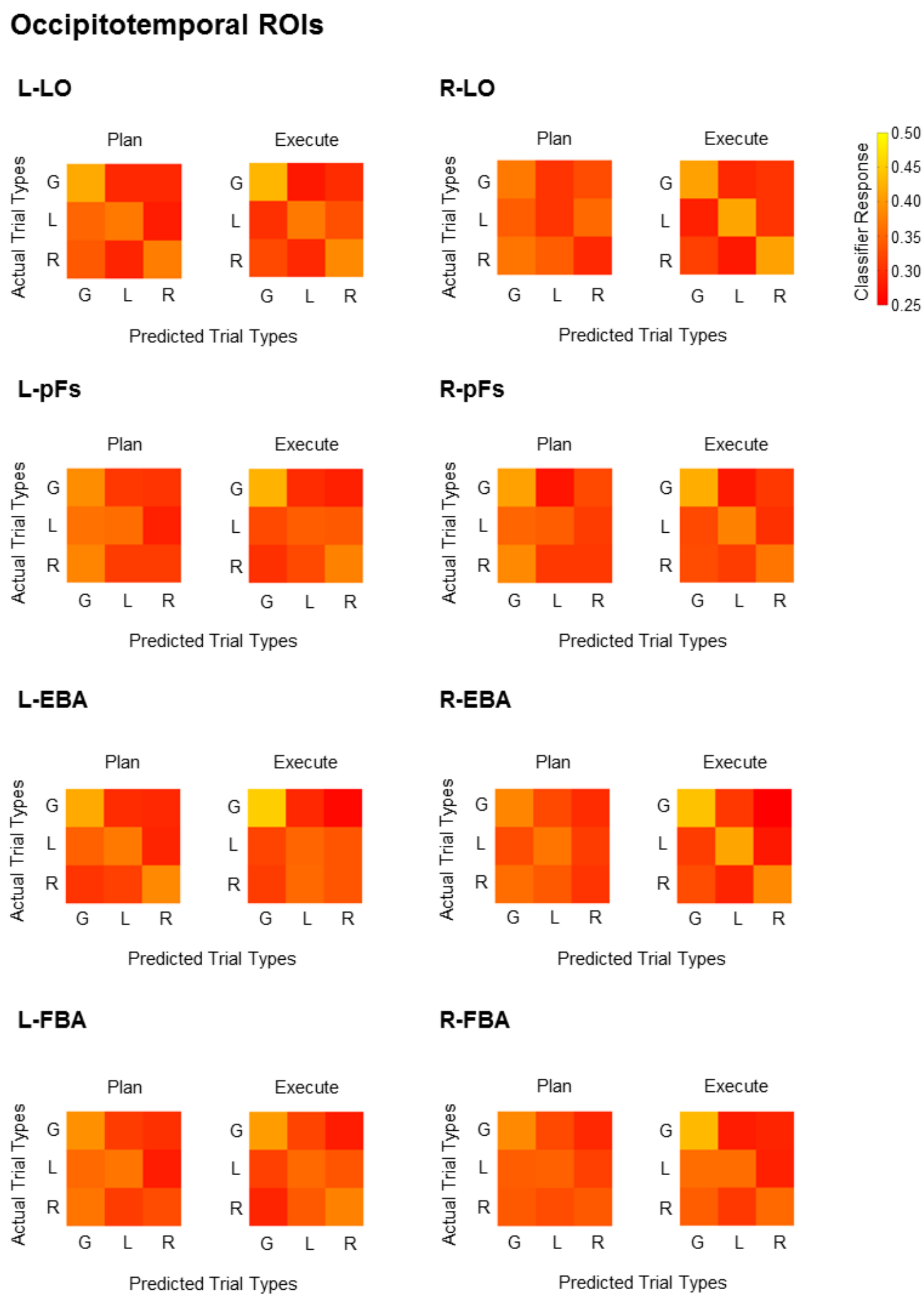

Figure S6: Confusion matrices generated from the multiclass discriminations in occipitotemporal cortex. Matrices are plotted and computed the same as in Fig. S5.

Mean ROI sizes across subjects from ACPC-aligned data

Brain Areas	mm^3	voxels
Frontoparietal cortex ROIs		
<u>Parietal Cortex</u>		
SPOC	2346.1	86.9
pIPS	2012.8	74.5
aIPS	2612.7	96.8
SSc	2687.2	94.5
<u>Frontal Cortex</u>		
M1	2569.4	95.2
PMd	2328.2	86.2
PMv	1669.4	61.8
SMA	2354.9	87.2
Occipitotemporal cortex ROIs		
<u>Object-selective areas</u>		
L-LO	1698.6	62.9
R-LO	1992	73.8
L-pFs	1500.8	55.6
R-pFs	1306.1	48.4
<u>Body-selective areas</u>		
L-EBA	1247.6	46.2
R-EBA	1971.5	73
L-FBA	844.8	31.3
R-FBA	983.8	36.4

Mean percentage voxel overlap between Localizer-defined Object- and Body-sensitive ROIs

Comparisons	No. Subjects	% Object ROIs	SEM
L-LO and L-EBA	7	21	7.3
R-LO and R-EBA	5	11.6	7.2
L-pFs and L-FBA	8	19.4	4.8
R-pFs and R-FBA	6	17.5	6.2

Table S1: Mean ROI sizes across subjects (N=14) and mean percentage voxel overlap between object- and body-selective OTC areas.

	Frontoparietal Brain Region							
	SSc	**SPOC**	**pIPS**	**aIPS**	**M1**	**SMA**	**PMd**	**PMv**
Multiclass Discrimination								
% Decoding	33.1	36.9	38.1	37.1	35.9	37.1	39.1	38.0
t-value	-0.148	2.994	2.744	3.163	2.386	2.349	6.045	6.299
p-value	0.885	0.010	0.017	0.007	0.033	0.035	<0.001	<0.001
Pairwise Discriminations								
G vs. PL								
% Decoding	48.4	54.2	55.3	53.7	53.4	55.5	56.4	54.0
t-value	-1.024	7.606	3.061	2.599	3.303	3.209	5.312	3.277
p-value	0.325	< 0.001	0.009	0.022	0.006	0.007	< 0.001	0.006
G vs. PR								
% Decoding	49.5	55.2	55.3	54.7	54.5	56.7	54.1	55.0
t-value	-0.352	4.487	2.881	3.939	4.802	5.078	3.052	4.678
p-value	0.730	0.001	0.013	0.002	<0.001	< 0.001	0.009	< 0.001
PL vs. PR								
% Decoding	50.4	52.7	54.6	52.6	55.3	53.9	55.6	52.5
t-value	0.395	1.381	3.605	1.751	3.473	2.799	3.958	2.149
p-value	0.699	0.190	0.003	0.104	0.004	0.015	0.002	0.051

Table S2: Statistics associated with the decoding analyses reported in Fig. 5. T-values degrees of freedom were equal to 13. G = Grasp-to-Hold, PL = Grasp-to-Place-Left, PR = Grasp-to-Place-Right.

	Occipitotemporal Brain Region							
	L-LO	**R-LO**	**L-pFs**	**R-pFs**	**L-EBA**	**R-EBA**	**L-FBA**	**R-FBA**
Multiclass Discrimination								
% Decoding	38.7	32.2	35.3	35.4	38.9	34.9	36.1	35.8
t-value	4.415	-0.788	1.435	2.366	5.616	1.062	1.984	2.577
p-value	0.001	0.445	0.175	0.034	<0.001	0.308	0.069	0.023
Pairwise Discriminations								
G vs. PL								
% Decoding	55.4	50.9	53.8	54.8	54.7	52.6	52.9	53.5
t-value	3.459	0.422	2.562	2.787	2.843	1.650	1.443	2.488
p-value	0.004	0.680	0.024	0.015	0.014	0.123	0.173	0.027
G vs. PR								
% Decoding	54.4	49.5	51.3	53.8	56.5	51.3	52.6	53.5
t-value	4.371	-0.305	0.776	2.539	5.041	0.769	1.386	2.899
p-value	0.001	0.765	0.452	0.025	<0.001	0.456	0.189	0.012
PL vs. PR								
% Decoding	56.7	48.2	53.3	53.0	53.5	50.0	53.6	54.0
t-value	4.033	-0.974	2.406	2.868	4.035	0.035	2.837	2.646
p-value	0.001	0.348	0.032	0.013	0.001	0.972	0.014	0.020

Table S3: Statistics associated with the decoding analyses reported in Fig. 6. T-values degrees of freedom were equal to 13. G = Grasp-to-Hold, PL = Grasp-to-Place-Left, PR = Grasp-to-Place-Right.

Brain areas	Trial Epoch	rm-ANOVA			Follow-up pair-wise comparisons	
		df	F-value	p-value	Comparison	p-value
Frontoparietal ROIs						
SPOC	Execute	1.474	7.134	0.008	G vs. PL	0.037
					G vs. PR	0.023
pIPS	Execute	1.977	6.001	0.007	G vs. PR	0.014
M1	Plan	1.648	4.625	0.027	G vs. PL	0.032
	Execute	1.414	5.086	0.026	---	---
PMd	Plan	1.538	4.520	0.032	L vs. PR	0.005
	Execute	1.410	5.375	0.023	---	---
SMA	Execute	1.641	8.223	0.004	G vs. PL	0.027
					G vs. PR	0.007
Occipitotemporal ROIs						
R-LO	Execute	1.970	4.328	0.024	---	---
R-EBA	Plan	1.495	4.168	0.042	---	---
R-FBA	Execute	1.639	4.134	0.037	G vs. PL	0.029

Table S4: Statistics associated with the univariate analyses reported in Fig. 8. Only statistically significant effects are reported. (---) denotes cases where none of the ANOVA follow-up pairwise comparisons reach statistical significance. Rm-ANOVA = repeated measures ANOVA; df = degrees of freedom; G = Grasp-to-Hold, PL = Grasp-to-Place-Left, PR = Grasp-to-Place-Right.

Confusion Matrices

To investigate the coding of object-directed action sequences in frontoparietal and occipitotemporal cortex in further detail, we next examined, based on the results of the multiclass discriminations, the distribution of classifier guesses via a confusion matrix (note that the confusion matrices are derived from the multiclass discriminations, not the pairwise discriminations; see Methods). In a confusion matrix, each row indicates the instances of the actual trial class (Grasp-to-Hold, Grasp-to-Place-Left or Grasp-to-Place-Right) and each column indicates the trial class predicted by the trained SVM classifier. Thus, the confusion matrix provides not just a visualization of the correct classifications (indicated by classifier responses along the diagonal axis) but also the cases of misclassification (i.e., where the trained classifier 'confuses' the actual trial class with that of another class, and indicated by the off-diagonal classifier responses). The distribution of misclassifications can be informative as it reflects similarity in the patterns of activity across trial types (i.e., two trial types represented similarly are more likely to be misclassified as one another), which is not wholly evident in the multiclass discrimination accuracies alone (i.e., the decoding accuracy bar plots). Although, in principle, statistical tests can be performed on the confusion matrices themselves to rigorously assess cases of misclassification, such statistical tests are unlikely to survive stringent corrections for multiple comparisons. For these reasons, we display the confusion matrices only to allow for qualitative comparisons of the classifier responses. Note that the lack of significant decoding in several areas during the Plan epoch (i.e., SSc, R-LO, R-EBA) makes any interpretation of the resulting confusion matrices irrelevant.

The confusion matrices for the frontoparietal and occipitotemporal ROIs (see Figs. S5 and S6) reveal that, in the Plan epoch, Grasp-to-Hold trials tended to be more reliably classified than those of the other two trial types, Grasp-to-Place-Left and Grasp-to-Place-Right (see top left box across all matrices). Interestingly, across a wide-range of areas including SPOC, pIPS, aIPS, M1, SMA, PMd, PMv, L-LO, L-pFs, R-pFs, L-FBA, and R-FBA we also found that, in the Plan epoch, both Grasp-to-Place-Left trials (second rows, across columns) and Grasp-to-Place-Right trials (third rows, across columns) tended to be more frequently misclassified as Grasp-to-Hold trials (see second and third rows of the leftmost column) than as the other type of Grasp-to-Place trial. At the outset, this pattern of misclassifications was not necessarily expected since Grasp-to-Place-Left and Grasp-to-Place-Right trials are much more similar in their movement complexity (i.e., movement duration, types of muscles used, types of actions performed) than each is to the simpler Grasp-to-Hold trials. In several areas (e.g., SPOC, pIPS, M1 and PMd), this distinct pattern of misclassifications during the Plan epoch appears to disappear during the Execute epoch, suggesting that the response properties of an area during execution may not be a reliable indicator of its responses properties during planning (see Churchland et al. 2010; Churchland et al. 2012 for examples from NHP neurophysiology; and see Shenoy et al. 2013 for review). To loosely speculate, perhaps during planning it is the end goals of the action sequence that are being most distinctly represented (resulting in more robust discriminations of Grasp-to-Place-Left vs. Grasp-to-Place-Right trials) compared to a representation of movement complexity (not such robust discrimination of the

Grasp-to-Place trials versus the Grasp-to-Hold trials) whereas during execution, it is movement complexity that is being more distinctly represented.