Supplemental Material

Human Posterior Parietal Cortex Plans Where to Reach and What to Avoid

Axel Lindner[1,*], Asha Iyer[1], Igor Kagan[1], Richard A. Andersen[1]

[1]California Institute of Technology, Division of Biology, Mail Code 216-76
1200 East California Boulevard, 91125 Pasadena, CA, United States
Tel.: +1 626 395-8336, Fax: +1 626 795-2397

[*]Corresponding Author: Axel Lindner (a.lindner@medizin.uni-tuebingen.de)
Present Address: Hertie Institute for Clinical Brain Research
Department for Cognitive Neurology, Hoppe-Seyler-Str. 3, 72076 Tübingen, Germany
Tel.: +49 7071 29-80469, Fax: +49 7071 29-5326

SUPPLEMENTAL DISCUSSION

Mnemonic task demands

On average, the same number of targets and the same amount of spatial precision was required in all three tasks under consideration. We presented cues at either two or four locations, and all nine potential locations were always visible during both the cue and the response phase, rendering a precise spatial memory for movement (in the DRT) unnecessary. A randomized and asymmetric arrangement of the potential target cues further helped to rule out that subjects could refer to a simple verbal memory strategy. Rather, our tasks required subjects to memorize the spatial positions of all visual cues or, alternatively, to remember the geometric target arrangement as a whole (i.e. subjects might have memorized a single "Gestalt"). However, the fact that we revealed fMRI activity that was significantly modulated by target load, irrespective of the actual experimental condition, highlights the notion that subjects remembered individual target locations rather than a single Gestalt (only). Moreover, it implies that the same mnemonic strategies were used in all three conditions.

SUPPLEMENTAL FIGURES

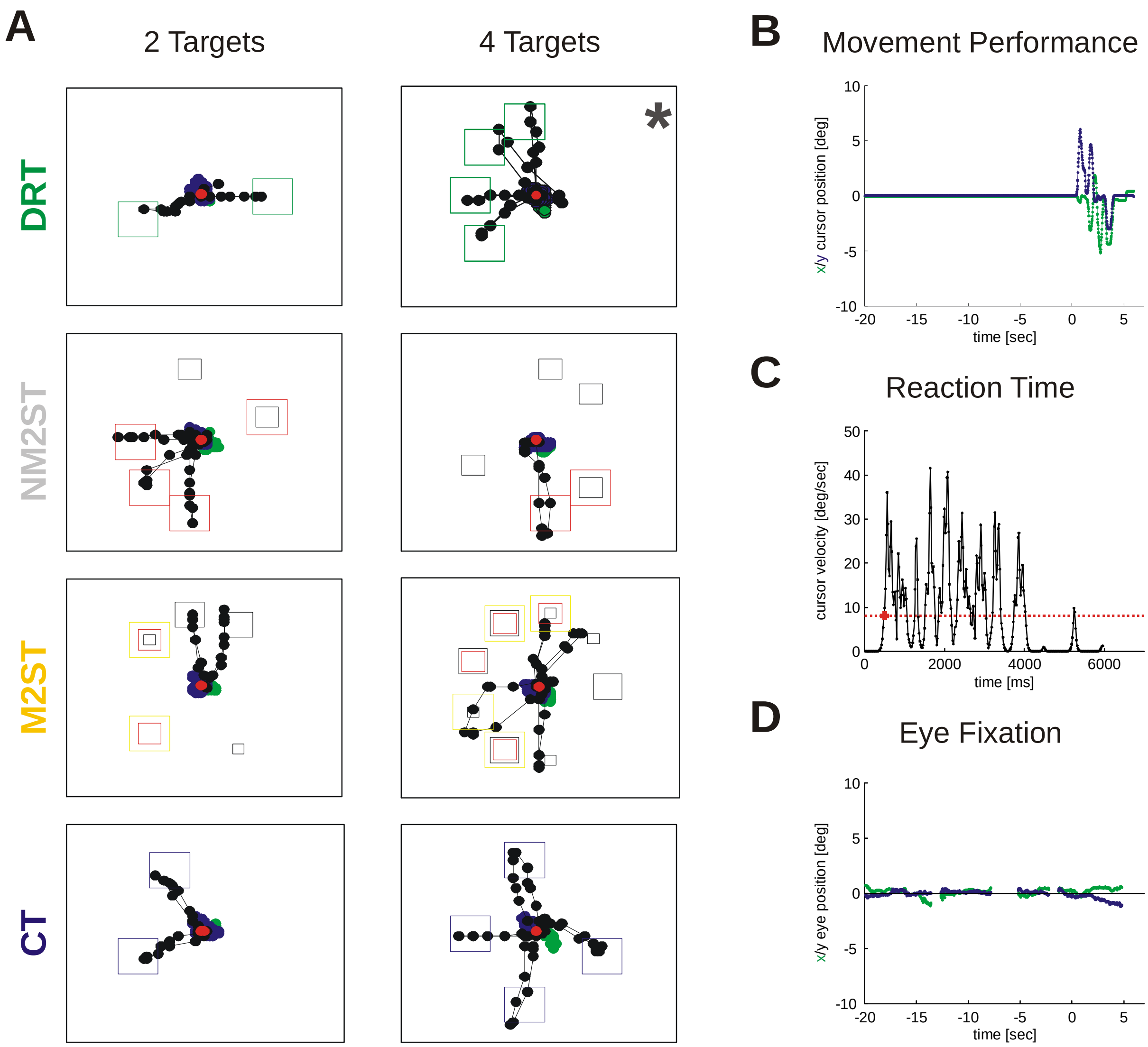
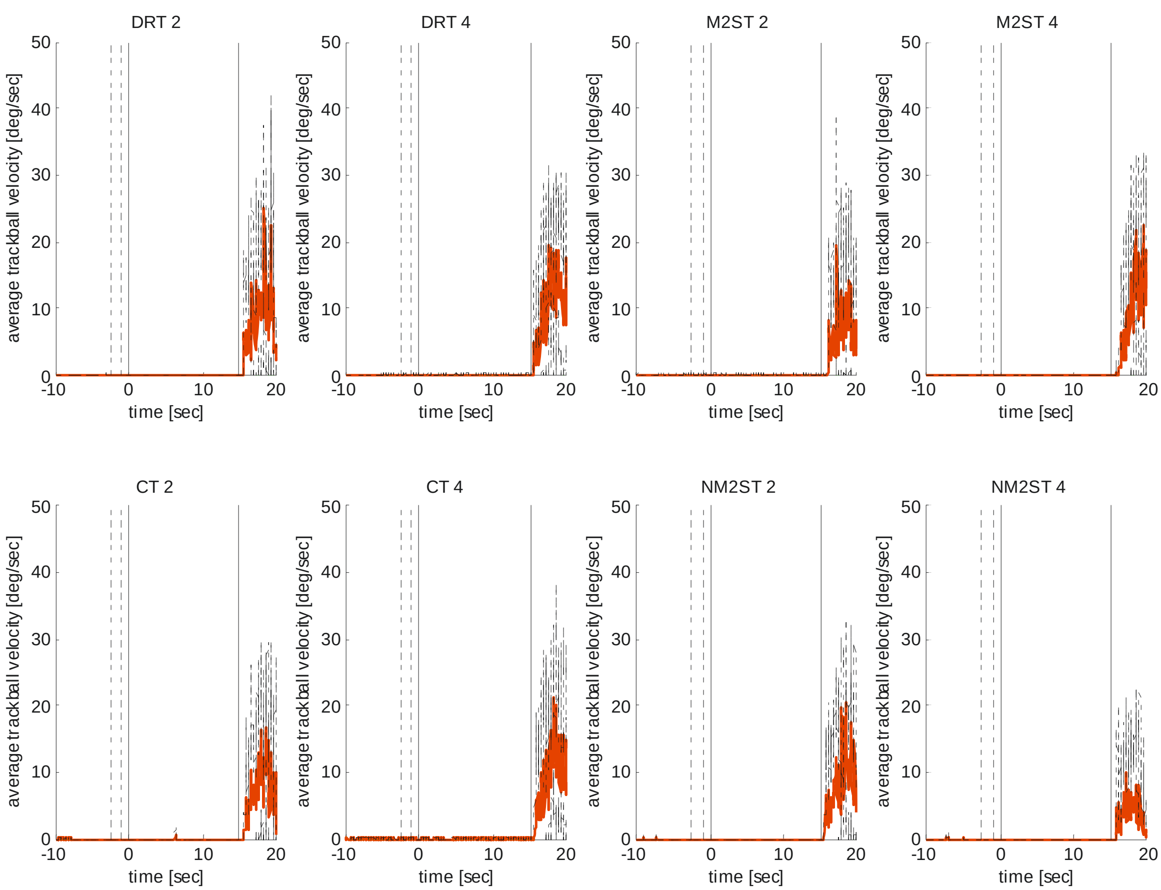


Figure S1. Representative Examples of Subjects' Performance

Eight examples of the different experimental conditions (4 tasks x 2 sets of target numbers, i.e. 2 or 4) are shown in **(A)**. Movement traces of the finger-guided cursor (in black) as well as gaze direction are overlaid (blue samples acquired during the delay phase, green samples were recorded during the response period). Note that in all conditions, this subject perfectly maintained central fixation throughout the trial. Green squares in the DRT indicate pre-cued movement goals. Black small squares in the

NM2ST indicate undesired target locations. Red squares show a second set of targets that were presented during the response period. In the response period subjects should perform movements to those targets of the second set that did not correspond to the previous cues (i.e. only towards the empty red squares). In the match-to-sample task (M2ST), small red squares represent the initial cues (sample) while the yellow squares represent the match stimulus. In case of a match, subjects had to go to the white targets of the response screen (large black squares). In case of a mismatch, they were required to reach at the black targets (small black squares). Note that the location of the response targets and the location of the match-to-sample targets were uncorrelated. In the CT subjects had to reach towards the targets presented in the response period. These targets are indicated as blue squares. **(B)** depicts the time-course of both horizontal (green) and vertical (blue) cursor position for the example in **(A)** that is indicated with an asterisk (DRT, 4 targets). This subject correctly performed a counter-clockwise sequence of finger reaches to all the four pre-specified targets. **(C)** shows the absolute velocity trace of the same movement aligned to the onset of the response period. The red broken line indicates the velocity threshold used to determine response onset (red dot). The horizontal (green) and vertical (blue) eye position traces are shown in **(D)**. Gaps in the eye records result from the rather frequent eye blinks of this particular subject.

A **Average Trackball Velocity of Representative Subject [deg/sec]**



B **Mean Trackball Velocity during Delay Period [deg/sec]**

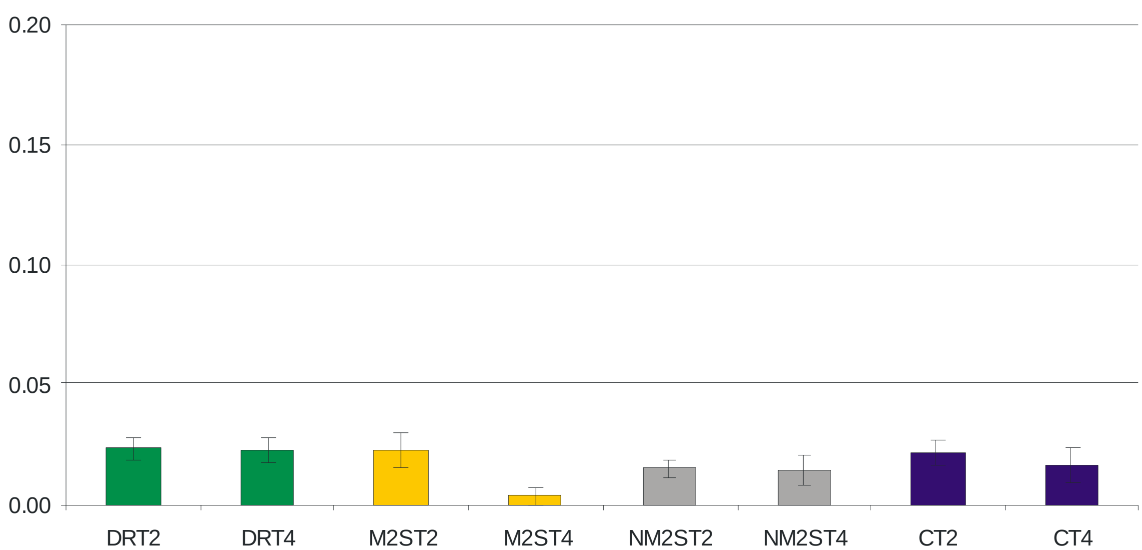


Figure S2. Trackball Movement During The Delay Period

The examples in **(A)** depict average absolute trackball velocity (+/-SE) of an exemplary subject. Time-courses are aligned to the onset of the memory delay, while the solid vertical lines indicate the average duration of the delay-epoch. Broken vertical lines denote the onset of the cues in the 4/2-target condition at -2.5s/-1.5s, respectively. As evident from the average velocity traces, significant trackball motion only occurred after the offset of the delay-period. The mean trackball velocity during the delay period (+/-SE), calculated across subjects' averages, is shown in **(B)**. As revealed by a 2-way repeated measures ANOVA there was no significant influence of either experimental condition (n.s.), target load (n.s.) or their interaction (n.s.). In other words, we did not detect any differences in delay-related trackball motion for our eight experimental conditions. This is important, since this finding further supports the notion that the differences observed in the sustained fMRI-responses cannot be accounted for by overt motor behavior.

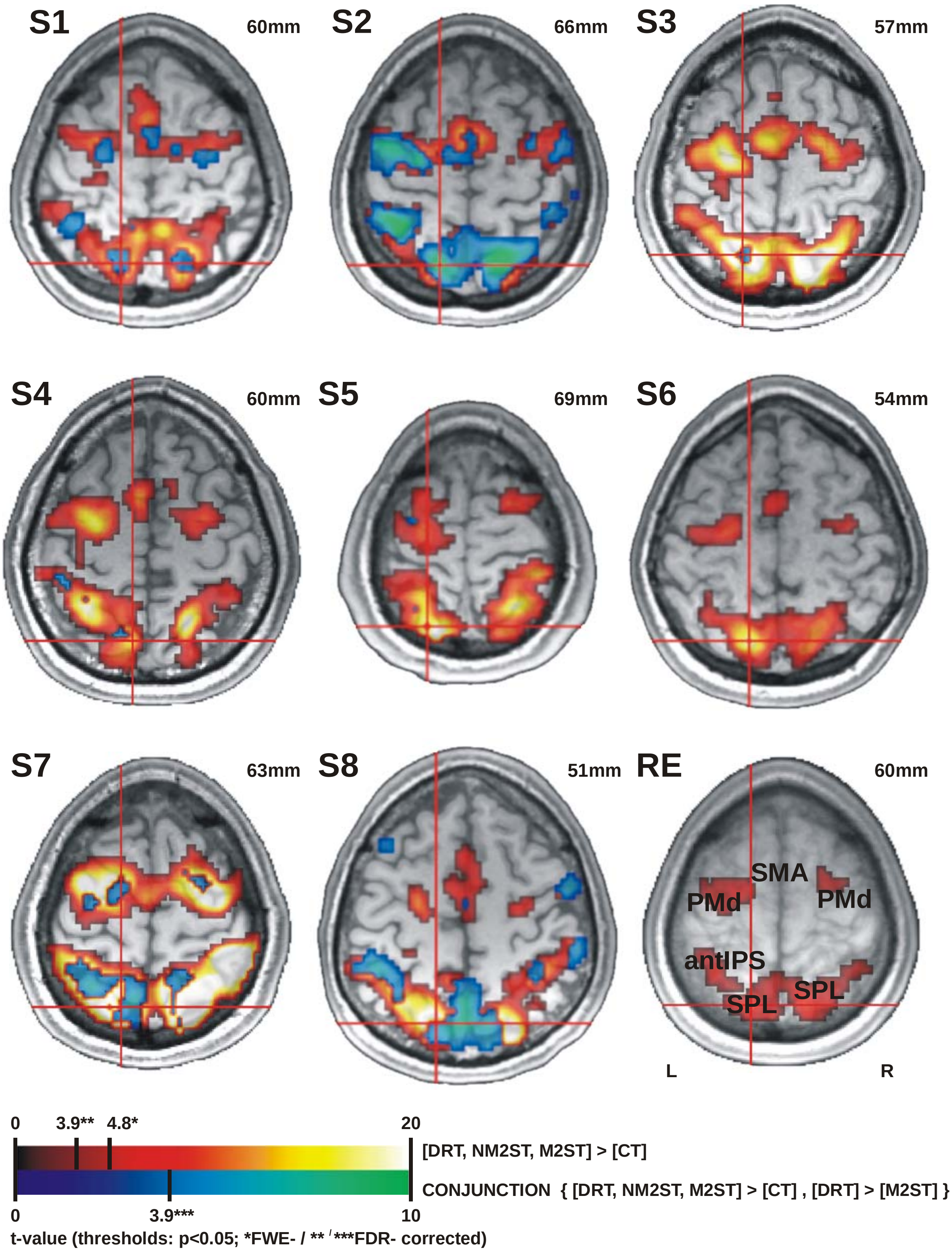
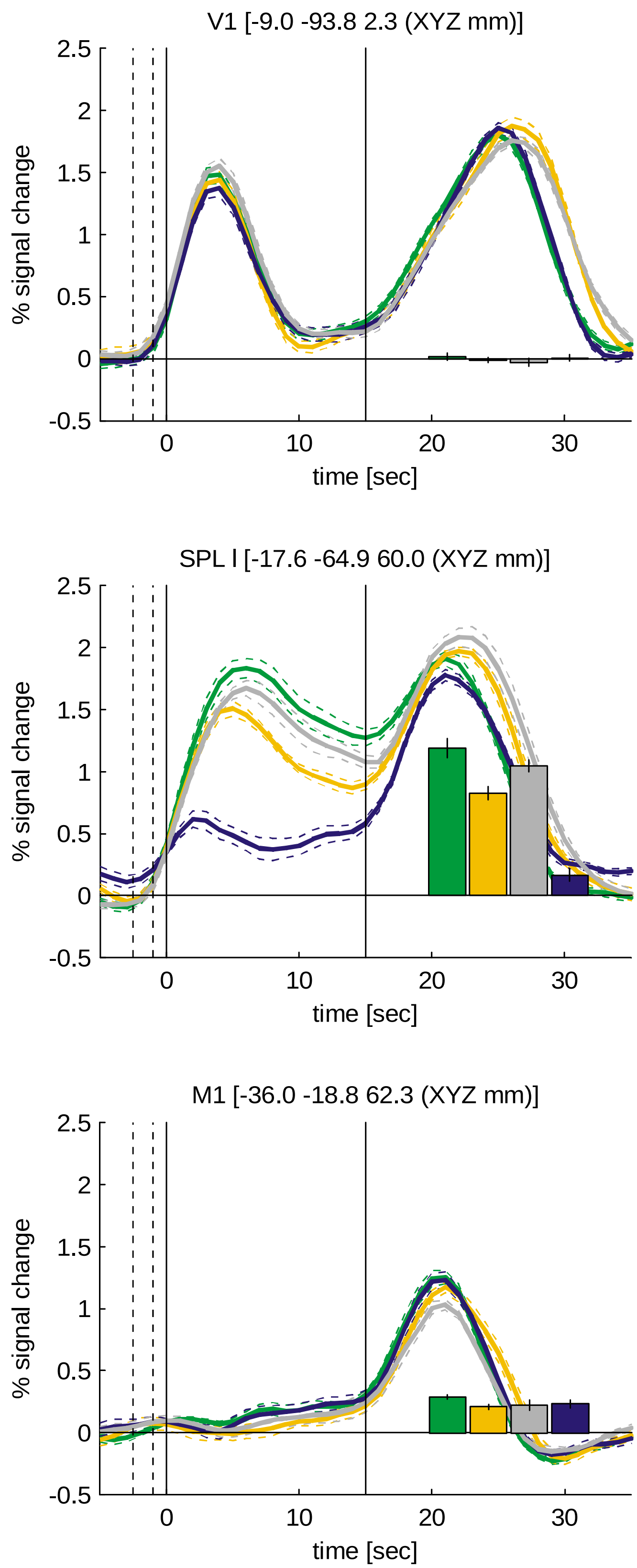

S1
60mm
S2
66mm
S3
57mm
S4
60mm
S5
69mm
S6
54mm
S7
63mm
S8
51mm
RE
60mm
SMA
PMd
PMd
antIPS
SPL
SPL
L
R
0
3.9**
4.8*
20
[DRT, NM2ST, M2ST] > [CT]
CONJUNCTION { [DRT, NM2ST, M2ST] > [CT] , [DRT] > [M2ST] }
0
3.9***
10
t-value (thresholds: p<0.05; *FWE- / ** / ***FDR- corrected)

Figure S3 Mapping Individual Subjects' ROIs: left SPL

The reddish statistical maps overlaid on the horizontal brain slices of individual subjects (S1-S8) depict areas that exhibited a significant delay-related increase in fMRI-signal amplitude in the test conditions (DRT, NM2ST, M2ST) as compared to the control task (CT; $p<0.05$, FWE-corrected *). This contrast was used to specify functionally defined ROIs in each individual. The corresponding statistical map of the random effects analysis across subjects is shown as RE ($p<0.05$ FDR-corrected **). In addition, the bluish maps indicate areas in individual subjects that showed both, delay-activity and a stronger BOLD-activation in the motor preparation condition (DRT) as compared to the memory condition (M2ST) in which such a specific motor preparation was impossible ($p<0.05$ FDR-corrected ***). The red cross-hairs point at the ROI which was individually mapped within each subject's left SPL and the corresponding region in the group analysis (RE). Yet, in order to allow a better comparison between the two activation maps (delay-activity and motor-planning), the z-level (mm) of the horizontal sections for subjects S4/S5 were shifted downward/upward by one voxel (3mm), respectively. Importantly, delayed fMRI-activity related to the prospective preparation of an upcoming movement (bluish map) could be demonstrated even within single subjects. Specifically, significant movement planning-activity within the left SPL could be mapped in 7 out of 8 individuals. Moreover, despite being centered on subjects' left SPL, horizontal sections show large parts of other delay- and movement planning- related parietal (right SPL, antIPS) and pre-motor areas (PMd and SMA).

Figure S4. Imaging Delayed fMRI-Activity



This figure illustrates how a delayed response task can be used to temporally separate delay-activity from visual and motor responses. The time-courses show the average fMRI-activity across subjects (+/- SE) for three different regions of interest (left primary visual cortex, V1 l; left superior parietal lobule, SPL l; and left primary motor cortex M1 l) and for our four principle conditions (DRT – green, M2ST – yellow, NM2ST – grey, CT – blue). Time-courses are aligned to the onset of the memory delay, while the solid vertical lines indicate the average duration of this delay-epoch. Broken vertical lines denote the onset of the cues in the 4/2-target condition at -2.5s/-1.5s, respectively. The average beta weights for the delay period (+/- SE) are further illustrated by the bars. Please note that in V1 l there is an initial peak of fMRI-activity, irrespective of the experimental condition. This peak is caused by the presentation of the visual cues and the mask, and it thus decays rapidly until time t=10sec after mask offset (i.e. delay onset). Only later, after the onset of the response screen at t=15sec (+/-1sec), fMRI activity in V1 l again rises due to visual stimulation. In contrast, fMRI activity in M1 l shows no initial peak. It ramps up slightly during the delay period and then rises steeply after the onset of the response screen, with a peak at about t=21sec (i.e. 5-6 sec after onset of the actual response). Finally, depicted in the middle panel, SPL l activity markedly differed from both V1 l and M1 l activity: it had significantly higher levels of sustained activity in the late delay period (t=10-15sec), which thus could be clearly temporally separated from both earlier "visual" responses (t<10sec; compare V1 l) and later motor responses (t>15sec; compare M1 l). Moreover, only SPL l exhibited fMRI-activity that differed between experimental conditions already before the onset of the motor response (or the response screen). Please note that these relative differences in the delay-related fMRI-activity (t=10-15sec), were accurately captured by the beta estimates of our GLM (see the respective bar plots and also refer to the results of the main manuscript). In contrast, no difference in the beta estimates emerged for both V1l and M1 l. This was supported by statistical analyses, which did not reveal any significant influence of the factor experimental condition (or the factor target load, or their interaction) on the beta estimates of either ROI (2-way repeated measures ANOVA, factors condition [n.s.], target load [n.s.] and interaction [n.s.]). The lack of significance of the factor target load in V1 further indicates that the different presentation times of the visual cues for the 2-target and 4-target conditions had no differential effect on the delay period estimates. In fact, in V1 none of the beta estimates captured any significant amount of fMRI-activity during the delay period (t-tests, one-tailed, n.s.). Both findings clearly demonstrate that there was no “carry-over” of visual activity, influencing the beta estimates of the delay period.

In summary, our experimental approach allowed us to isolate fMRI-activity related to the (late) delay-epoch - even without the need for signal deconvolution. Yet, an obvious limitation of this approach is the fact that it requires planning that is constant or at least long enough to be captured at this late stage. The fact that we were still able to detect prospective planning during the late delay might thereby relate to an optimized task design: longer durations of planning and reiteration were imposed by instructing sequences of out-and-back movements rather than single, center-out reaches.

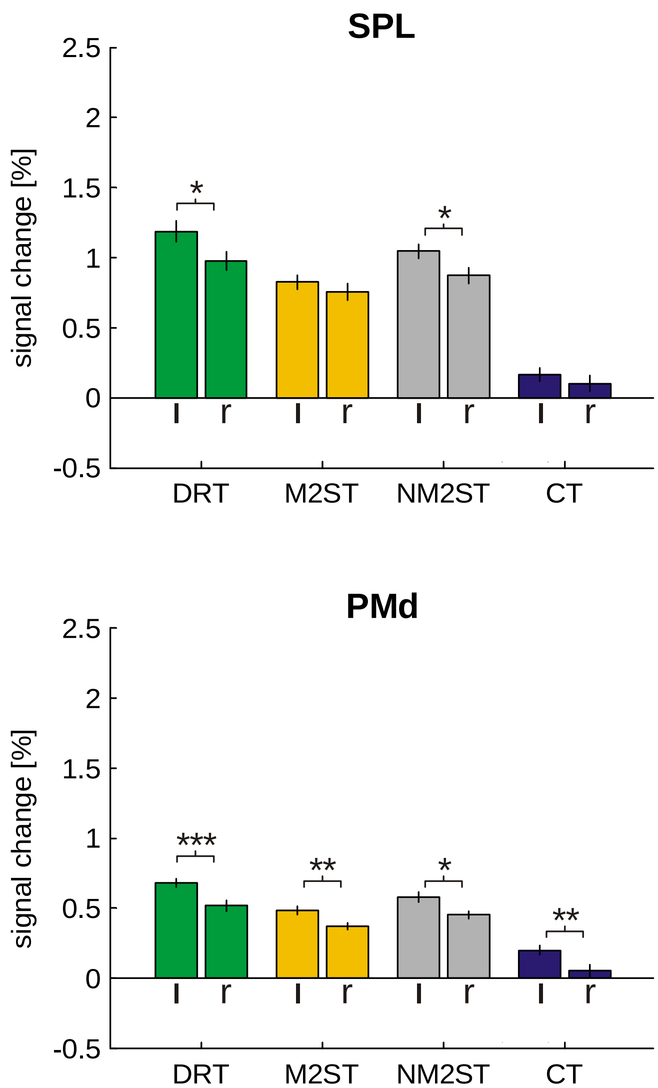


Figure S5. Cross-Hemispheric Differences in Areas SPL and PMd

This figure depicts the average beta-estimates of the delay-related fMRI-activity for our principle experimental conditions and for the left (l) vs. the right (r) SPL and PMd, respectively. Significant cross-hemispheric differences of the beta estimates are indicated by asterisks (* p<0.05, ** p<0.01, *** p<0.001; paired t-tests). In SPL significant differences emerged only in the prospective planning conditions (DRT and NM2ST), while higher levels of delay-related activity were obtained for the left hemisphere, i.e. contralateral to the effector. This pattern of activity thereby supports a role of SPL in prospective movement planning. In contrast, PMd exhibited the same effect of contralaterality with respect to the effector, but in all experimental conditions. This effect is most likely explained by its stronger contribution to unspecific movement preparation, common to all conditions. Note, however, that this finding does not disprove an additional role of PMd in the prospective planning of behavior, as signified by the differences in sustained fMRI-activity between the DRT (or the NM2ST) and the M2ST.