SUPPLEMENTAL INFORMATION

Corticostriatal output gating during selection from working memory

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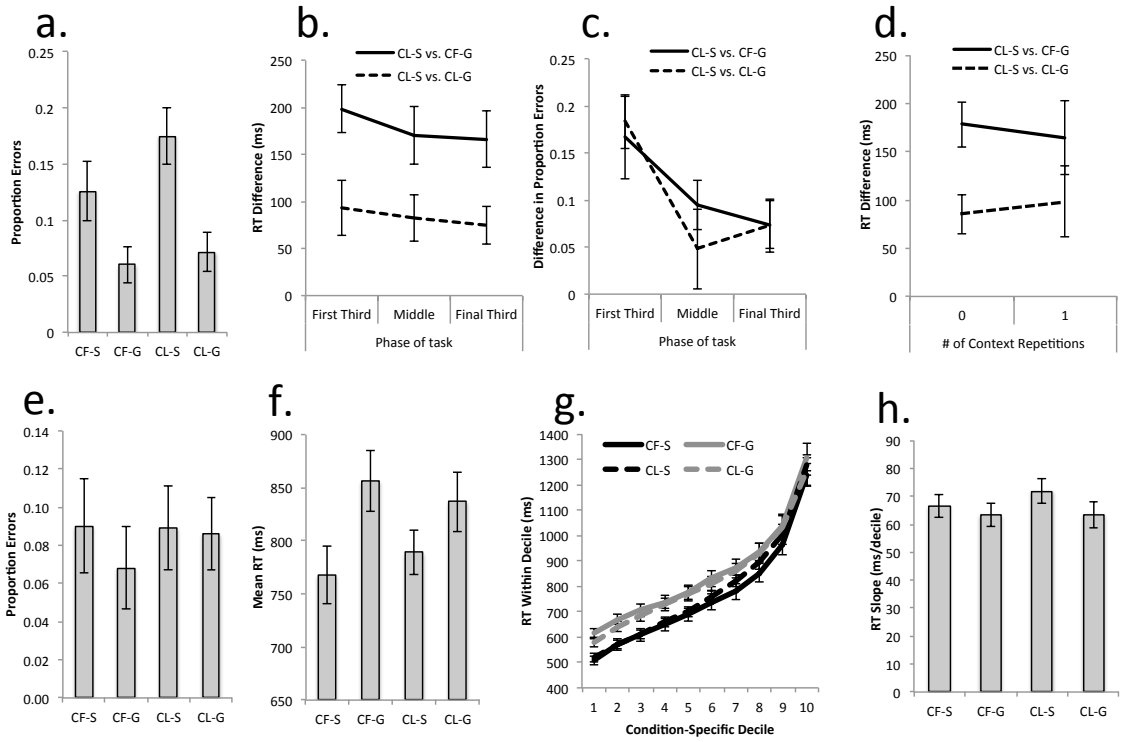

Figure S1: Behavioral costs due to output gating are also evident in errors, and stable across the task; related to Figure 2. (**a**) Errors were disproportionately increased during the CL-S condition, relative to the load-matched CF-G and CL-G conditions, akin to the RT effects described in the main text. (**b & c**) Across the course of the experiment, the CL-S condition was associated with elevated RT (**b**) and errors (**c**) relative to its load-matched input gating control (CF-G) and its load-matched output gating control (CL-G), suggesting the difficulty of selective output gating is not due to insufficient practice with the rule. RT also remained elevated in successive experiences with the same rule (**d**), indicating the difficulty in the CL-S condition was not due to difficulty experienced in retrieving the meaning of each selective context. (**e**) The presentation of response mappings as a separate event eliminated all differences in error rate between conditions (F's<1.4 p's>.258). (**f**) The RT differences across conditions were also affected by the change in timing of response mappings: despite a significant effect of selective vs. global contexts on RT ($F(1,21)=22.78$, $p<.001$), there was no significant effect of order ($F(1,21)=.007$, $p>.9$) and only a marginal interaction of these factors ($F(1,21)=3.38$, $p=.08$). (**g**) Inspection of the decile plots revealed this marginal interaction might be attributed to the summation of two very slight effects: an elevation of the tail of the RT distribution during selective contexts presented last, relative to first; and a reduction in the leading edge of the RT distribution during global context presented last, relative to first. However such changes did not translate into significant interactions in terms of RT Slope (**h**). Instead, RT Slope showed only a marginal main effect of selective vs. global ($F(1,21)=3.68$, $p=.07$), without a main effect of presentation order ($F(1,21)=1.11$, $p=.3$) or interaction ($F(1,21)=.96$, $p=.38$). The clear differences between selective and global contexts independent of order is consistent with either the role of differences in working memory load or of the demand to perform conjunction as opposed to singleton match during the response process.

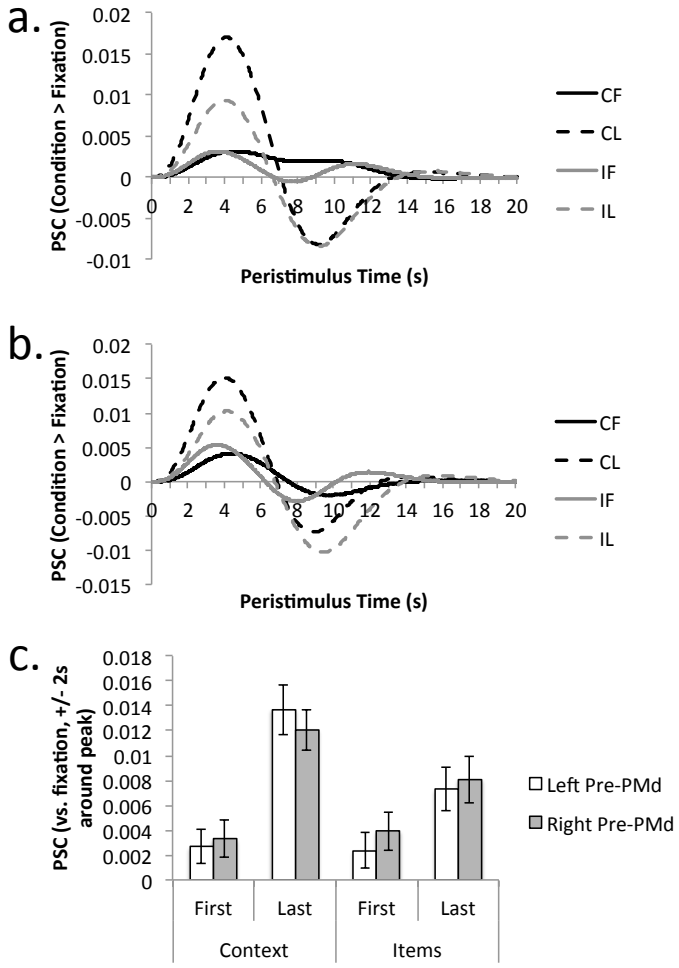

Figure S2: Timecourses from flexible hemodynamic response model in an unbiased, *a priori* ROI in the left (a) and right (b) PrePMd, as a function of stimulus order (first vs. last) and type (context vs. items), and estimates of PSC derived from their peaks (c); related to Figure 4. **A.** The hemodynamic responses elicited by higher-level Context when presented last [CL] were larger in the left pre-PMd than those elicited by higher-level Context when presented first [CF], and this difference was greater than that observed between Items when presented last [IL] as opposed to first [IF]. **B.** The same pattern of effects observed in the left pre-PMD was also evident in the right pre-PMd. **C.** PSC was calculated in the range of +/- 2s around the condition-specific peak of the hemodynamic response as estimated from the timecourses plotted in A & B. The 2 (stimulus type: Context vs. Items) x 2 (order: First vs. Last) x 2 (hemisphere: left vs. right) RM-ANOVA reported in the main text revealed that the effect of order on PSC reliably differed by stimulus type across both left and right pre-PMd, with no significant effect of hemisphere.

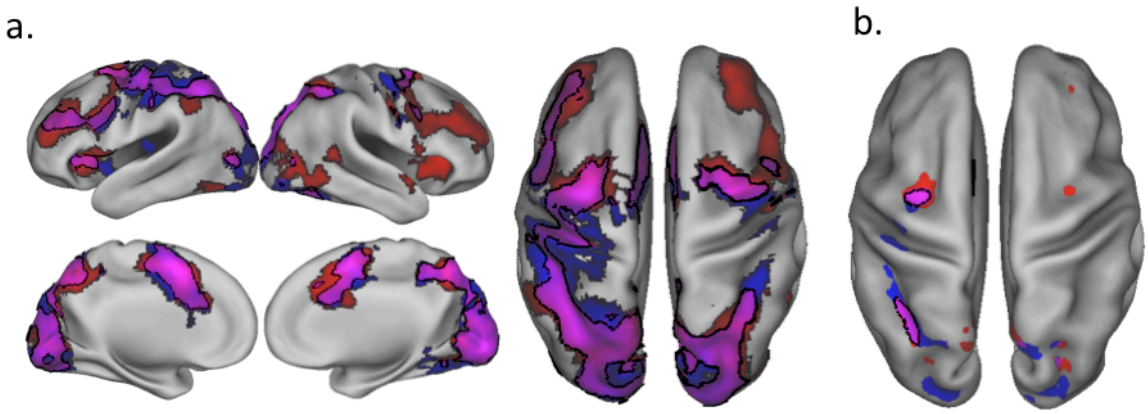

Figure S3: Sustained cortical responses to context; related to Discussion. Reynolds et al. (2012) proposed that prior manipulations of second-order control might have elicited activation related to both encoding and maintenance demands, whereas first-order control tasks might have required only encoding, and that these differences might produce functional dissociations between pre-PMd and PMd. Results in the main text show the pre-PMd can be more strongly recruited for contextual information that need not be maintained at all (as in CL) than conditions clearly requiring maintenance (i.e., CF). Conversely, sustained responses to context are observed (**a**) when transient events are modeled with FLOBS (see Experimental Procedures and main text) in both the selective (red) and global (blue) contexts. Areas where significant effects were observed in both conditions are shown in magenta with black outlines. (**b**) When a more conservative voxel-wise threshold equivalent to $p<.0001$ is applied, post-hoc, to (a), the frontal peak of the sustained response common to the selective and global contexts clearly lies within the left dorsal pre-motor cortex (PMd, black outlined region). The current results thus suggest that the source of discrepancies between studies may not be due solely to differing demands on maintenance between first and second-order control.

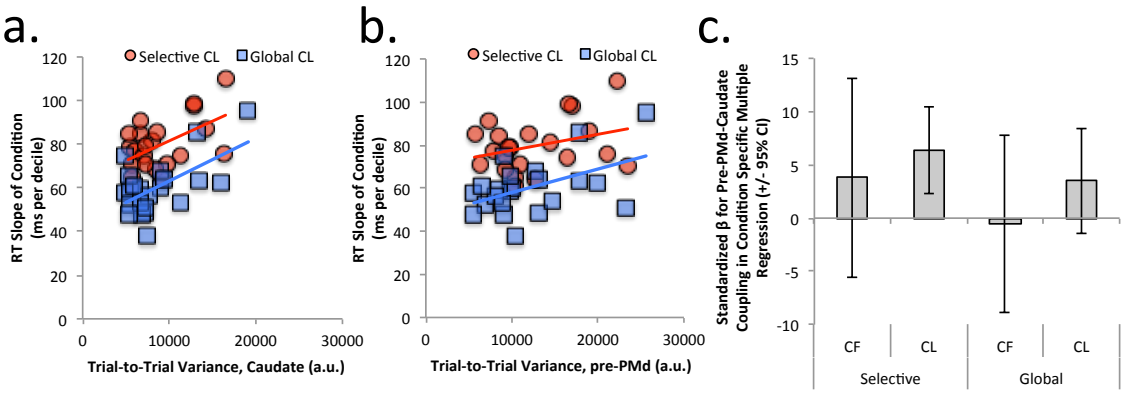

Figure S4: Trial-to-trial variance in caudate and pre-PMd predict RT slope, independently from coupling; related to Discussion. One significant source of elongations to the RT distribution during output gating is trial-to-trial variance within regions implicated in task performance, but this cannot fully explain the relationship of pre-PMd-caudate coupling to elongations of the RT distribution during selective output gating. (**a**) Median estimates of trial-to-trial variance across voxels in the anatomically-defined bilateral caudate during each condition were significantly correlated with measures of RT slope in the corresponding conditions only for CL (selective R=.52, p=.01; global R=.59, p<.005; CF p's>.05), even after controlling for mean RT in those conditions (selective: R=.52, p<.02, global R=.60, p<.005). By contrast, mean RT showed no significant correlations with trial-to-trial variance in any condition (all p's>.4). (**b**) In the *a priori* pre-PMd, median estimates of trial-to-trial variance across voxels only in the CL-G condition significantly correlated with measures of RT slope (R=.48, p<.05; all other p's>.14), even after controlling for mean RT in that condition (R=.48, p<.05), though again there were no significant correlations of mean RT with trial-to-trial variance in pre-PMd recruitment in any condition (all p's>.17). (**c**) Critically, trial-to-trial variance in both bilateral pre-PMd and caudate recruitment did not explain the relationship of bilateral pre-PMd-caudate coupling to RT slope in the CL-S condition, as indicated by the significant parameter estimate for coupling in a multiple regression ($F(1,18)=10.86$, p<.005; units reflect increases in slope per standard deviation change in coupling) in that condition alone (p's >.15 for coupling's relationship to slope independent of trial-to-trial variance in pre-PMd and caudate in multiple regressions specific to each other condition).

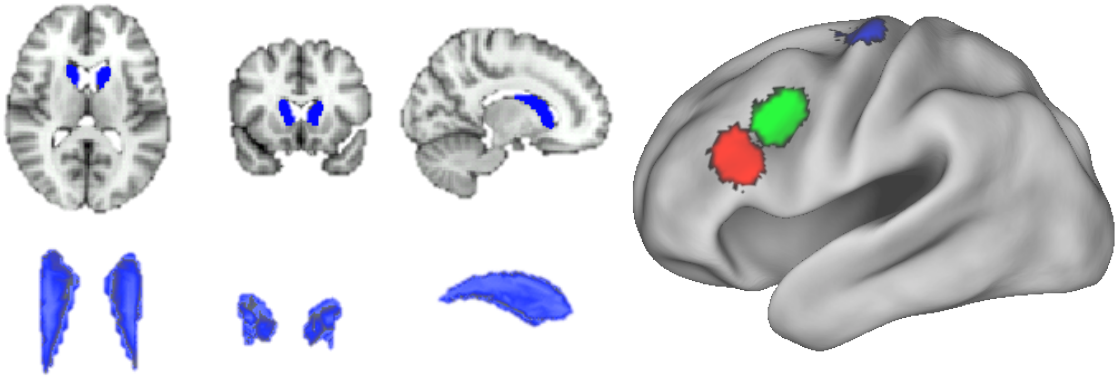

Figure S5: Regions of interest; related to Experimental Procedures and Results. Location of caudate (volumetric render); IFS (surface render, red), PrePMd (surface render, green) and PMd (surface render, blue) a priori regions of interest.

Table S1: Global and local maxima of clusters that GRF-correct to p<.05.*

Contrast	Voxels	Peak Z	Center of Gravity (XYZ [mm])	BA	Local Maxima (XYZ [mm])
Context > Item	9912	5	-10,-65,39	7	-8,-74,44 (Precun.) -36,-50,42 (IPS) -36,-56,50 (IPS) -18,-70,46 (Cerebellum) -42,-52,38 (SMG) -34,-74,48 (LOC)
	5267	4.69	-28,7,45	6	-28,-6,56 (PMd) -28,4,60 (PMd) -48,30,24 (IFS) -30,8,60 (pre-PMd) -28,12,56 (pre-PMd) -48,26,32 (IFS)
	1253	3.85	30,7,47	6/9	22,2,48 (PMd) 28,4,58 (PMd) 46,28,30 (IFS) 28,10,44 (PMd) 36,2,54 (PMd) 32,12,52 (Pre-PMd)
Item > Context	792	3.77	36,20,-21	47	34,24,-22 (OFC) 48,26,-22 (OFC) 32,32,-22 (OFC) 28,22,-26 (OFC) 22,10,-24 (lat OFC) 50,32,-20 (lat OFC)
CL > CF	25511	5.78	-7,-70,18	18	-48,-38,46 (IPS) -42,-42,40 (IPS) 32,-74,-22 (Cerebellum) -32,-78,-18 (LOC) -24,-72,46 (LOC) -30,-58,46 (IPS)
	7065	5.59	-33,12,36	6	-50,8,30 (pre-PMd) -46,28,32 (IFS) -32,-4,62 (PMd) -28,-6,48 (PMd) 0,14,44 (pre-SMA) -18,4,66 (PMd)
	2662	4.06	37,28,28	9/46	30,56,12 (RLPFC) 34,-2,38 (pre-PMd) 36,0,60 (PMd) 38,46,22 (RLPFC) 30,58,-4 (RLPFC) 30,0,48 (PMd)

	718	3.57	-3,-17,8	Thal	-4,-34,22 (Post. Cing) 4,-8,-2 (Thalamus) -10,-28,14 (Thalamus) -22,-16,6 (Pallidum) 14,4,-4 (Pallidum) -10,-18,8 (Thalamus)
CF > CL	1671	3.86	-4,52,0	10	0,60,-2 (OFC) -12,48,-10 (OFC) -2,48,-18 (OFC) 2,64,18 (OFC) -6,62,20 (OFC) -2,46,-8 (OFC)
Item Last > Item First	28134	5.53	-1,-73,15	18	-2,-90,24 (Occ) -34,-70,-20 (LOC) -34,-76,-20 (LOC) -34,-94,14 (LOC) -26,-80,-18 (LOC) 34,-74,-14 (LOC)
	2409	4.11	37,21,38	9/46	38,46,24 (RLPFC) 36,46,28 (RLPFC) 48,24,34 (pre-PMd) 30,4,58 (PMd) 26,2,48 (PMd) 32,-6,48 (PMd)
	1462	3.98	-35,3,45	6	-50,8,30 (pre-PMd) -28,-6,46 (PMd) -30,-2,64 (PMd) -20,0,68 (PMd) -20,8,58 (PMd) -14,8,62 (PMd)
	1369	3.73	-37,38,25	46	-32,46,30 (RLPFC) -46,28,34 (IFS) -46,32,24 (IFS) -54,26,32 (IFS) -40,24,26 (IFS) -30,44,22 (RLPFC)
Item First > Item Last	1233	3.6	-3,54,3	10	-10,44,18 (OFC) 4,68,12 (OFC) 4,66,-4 (OFC) 2,62,18 (OFC) -10,48,-12 (OFC) 2,60,-10 (OFC)
[Context Last > First] > [Item Last > First]	2229	4.18	-38,-48,43	40	-48,-36,44 (IPS) -44,-42,40 (IPS) -38,-46,42 (IPS) -26,-58,38 (LOC) -38,-28,40 (IPS) -38,-66,56 (SPL)
	1783	4.25	-41,5,42	6	-52,6,38 (pre-PMd) -48,26,28 (IFS) -28,-2,60 (PMd) -24,-8,56 (PMd) -34,-6,48 (PMd) -36,-12,36 (PM)

* Approximate anatomical locations are abbreviated as follows. OFC: orbitofrontal cortex; LOC: lateral occipital cortex; SPL: superior parietal lobe; IPS: intraparietal

sulcus; PMd: dorsal premotor cortex; PM: premotor cortex; pre-PMd: dorsal pre-premotor cortex; IFS: inferior frontal sulcus; RLPFC: rostrolateral PFC; OCC: occipital cortex; Precun: precneus; Post. Cing: posterior cingulate; SMG: supramarginal gyrus; RLPFC: rostrolateral PFC

Table S2: Key Brain-Behavior Correlations Using Alternative Measures of Spread

		Pearson R for Measure of Spread (in CL-S condition)		
Hemodynamic Response (to Context in CL-S)	Partialling…	RT Slope	RT Slope (mid)[1]	Inter-Decile Range
Bilateral Caudate PSC	n/a (zero-order correlation)	**-0.532****	**-0.46****	**-0.44****
	Caudate PSC & RT in other conditions	-0.354	**-0.551****	-0.293
	Pre-PMd PSC	**-0.564****	**-0.464****	-0.35
	Pre-PMd-caudate coupling	**-0.504****	**-0.383***	**-0.412***
Bilateral Pre-PMd-caudate coupling	n/a (zero-order correlation)	**0.561****	**0.481****	**0.53****
	pre-PMd-Caudate coupling & RT in other conditions	**0.511****	**0.379***	0.254
	Pre-PMd PSC	**0.552****	**0.521****	**0.471****
	Caudate PSC	**0.535****	**0.493****	**0.437****

** p<.05
* p<.1

[1] This is RT Slope as calculated only across the 3rd to 7th deciles (i.e., RT Slope$_{mid}$), to assess whether RT Slope effects replicate when excluding the non-linear extremes of the decile plots.

Supplemental Experimental Procedures

S1: Experimental procedure for instructing subjects to perform behavioral task

"In this task you will only press two buttons – either the 'f' or 'j' key – on each trial. You will only do so after you see three items. One of the items will always be a digit (either 1, 2 or 3), one will be a letter (either A or B) and the other will be a symbol (either a sun or a snowflake). These items can appear in random order but this makes the task difficult - the digits are particularly important. The digits tell you what other items to attend to. If you see a '1' as part of the three items that make up a trial, all that matters is what symbol you see. Whether you see an A or a B doesn't matter, so you can forget that information if it has already appeared by the time you see a 1, or you can prepare to ignore it when it appears. Conversely, if you see a '2' as the digit on that trial, you will only need to attend to the letter on that trial, and whether you see a sun or a snowflake doesn't matter, so you can forget or ignore that information. Finally, if you see a '3', you will need to remember both what letter and what symbol you see. Along with the final item in each trial, whatever that may be, you will see a letter and symbol at the bottom left, and a letter and symbol at the bottom right. Press the 'f' key if the relevant item or items appear on the left side; press the 'j' key if the relevant item or items appear on the right."

Several trials were then demonstrated to each subject, and it was emphasized that correct responses in the global conditions could only be determined by finding the conjunction of both the lower-level items that occurred on each trial.

S2: Experimental procedures for establishing specificity and independence of brain-behavior correlations

As noted in the main text, PrePMd PSC during contexts in the CL-S condition was correlated with mean RT observed in the same condition. This correlation was significant in both hemispheres. Thus, as noted in Methods, we averaged each subject's PrePMd across hemispheres, to more powerfully and reliably assess whether this shared variance was specific to the CL-S condition. As a next step, we isolated variance in bilateral PrePMd PSC that was unique to selective contexts appearing last (i.e., isolating it from variance in PrePMd PSC that was shared across contexts of different types/orders). This was accomplished by multiple regression of PrePMd PSC during CL-S contexts on the PrePMd PSC during contexts in every other condition (CF-S, CF-G, and CL-G), and by saving the residuals of this regression. The equivalent procedure was used to isolate any variance in mean RT that was unique to the CL-S condition (i.e., by regressing CL-S mean RT on mean RT from every other condition, and saving the residuals). The residuals of these two regressions were then correlated (and reported in the main text and shown in Fig. 4e). This correlation (formally, a semi-partial correlation) indicates that there is variance unique to the CL-S condition that is shared across both brain and behavior.

Fundamentally analogous approaches were used to calculate all correlations described in the main text used to motivate claims regarding the specificity and

independence of our brain-behavior correlations. For example, to assess whether bilateral PrePMd PSC during CL-S contexts was independent of PSC in the adjacent PMd and IFS during the same events, we regressed bilateral PrePMd PSC during CL-S contexts on each and saved the residuals. These residuals were then correlated with mean RT in the CL-S condition (again, a semipartial correlation).

Likewise, to assess the specificity and independence of the bilaterally-significant correlation between caudate PSC to contexts in the CL-S condition and RT Slope in the same condition, we averaged each subject's caudate PSC across hemispheres. We then isolated variance in bilateral caudate PSC that was unique to contexts in the CL-S condition by regressing it on bilateral caudate PSC observed to contexts in the other conditions, and saving the residuals. We next isolated variance in RT Slope unique to the CL-S condition by regressing it on RT Slope measured in the other conditions and saving those residuals. Finally, these two sets of residuals were then tested for a correlation (and reported in the main text and shown in Fig. 4h).