Cell Reports, Volume 42

Supplemental information

Cross-task specificity and within-task

invariance of cognitive control processes

Yuchen Xiao, Chien-Chen Chou, Garth Rees Cosgrove, Nathan E. Crone, Scellig Stone, Joseph R. Madsen, Ian Reucroft, Yen-Cheng Shih, Daniel Weisholtz, Hsiang-Yu Yu, William S. Anderson, and Gabriel Kreiman



Figure S1. Accuracy and difficulty of tasks. A-C. Accuracy of each task by each subject. Black bars indicate congruent trials and red bars incongruent trials. **D**. Average accuracy across all subjects. Error bars indicate s.e.m. Asterisk indicates statistically significant difference between congruent and incongruent conditions (p=0.001, n=16, permutation test, 10,000 iterations). **E**. There was no difference among the three tasks in task difficulty calculated as the ratio of reaction times of incongruent to congruent trials (p=0.16, one-way ANOVA). Asterisks denote significant differences in each task with respect to the null hypothesis corresponding to a ratio of 1 (permutation test, 10,000 iterations, $\alpha=0.05$).



Figure S2. Alignment to stimulus and behavioral response is critical to interpret conflict modulation signals. An electrode in the right lateral occipital cortex showed conflict modulation when the high-gamma power (mean±SEM, black for congruent and red for incongruent) was aligned to behavioral response (**A**) but no such effect emerged when aligned to stimulus onset (**B**). Conversely, an electrode at the right precentral gyrus showed conflict modulation when the high-gamma power (mean±SEM) was aligned to stimulus onset (**D**) but not behavioral response (**C**). These electrodes reflect either purely visual response (**B**) or purely motor response (**C**) and were thus not considered as conflict-selective.



Figure S3. Example Flanker-specific electrode in the high gamma band (same electrode as in Figure 5A). An electrode located in the right superior parietal cortex exhibited conflict modulation in the Flanker task only. A. Raster plots showing the neural signals in individual trials (see color scale on the right) for congruent and incongruent trials. The white dashed lines in the raster plots show the average stimulus onset time (these lines are shifted to the left in incongruent condition compared to congruent condition, indicating longer RT for the incongruent trials). Gray and white bars on the left of the raster plots represent different blocks. B. Z-scored high-gamma power (mean±SEM, black for congruent and red for incongruent) aligned to stimulus onset. Vertical dashed lines denote the average behavioral response time. Yellow background indicates statistically significant difference between congruent and incongruent trials (permutation test, 5000 iterations, alpha=0.05, Methods).



Figure S4. Example Number-specific electrode in the high-gamma band (same as in **Figure 5B**). An electrode located in the right precuneus exhibited conflict modulation in the Number task only. **A**. Raster plots showing the neural signals in individual trials (see color scale on the right) for congruent and incongruent trials. The white dashed lines show the average stimulus onset time (these lines are shifted to the left in incongruent condition compared to congruent condition, indicating longer RT for the incongruent trials). Gray and white bars on the left of the raster plots represent different blocks. **B**. Z-scored high gamma power (mean±SEM, black for congruent and red for incongruent) aligned to stimulus onset. Vertical dashed lines denote the average behavioral response time. Yellow background indicates statistically significant difference between congruent and incongruent trials (permutation test, 5000 iterations, alpha=0.05, **Methods**).



Figure S5. Example Stroop-specific electrode in the theta band (right pars triangularis). A. The traces show the mean±SEM z-scored theta (4-8 Hz) power aligned to behavioral response time for incongruent trials (red) and congruent trials (black) for each of the three tasks (Column 1: Stroop; Column 2: Flanker; Column 3: Number). The vertical dashed lines denote the average stimulus onsets. Yellow background indicates statistically significant power difference between congruent and incongruent trials (permutation test, 5,000 iterations, α =0.05, Methods). Legend shows the number of congruent (C) and incongruent (I) trials. The electrode location is shown on the right. **B**. Raster plots showing the neural signals in individual trials (see color scale on the right) for congruent and incongruent trials. The white dashed lines show the average stimulus onsets. Gray and white bars on the left represent different blocks. **C**. Z-scored theta power aligned to stimulus onset. Vertical dashed lines denote the average behavioral response times.

A High gamma band



B Theta band



Figure S6. Electrodes exhibiting conflict modulation in high-gamma (A) or theta (B) band. Specific locations of these electrodes can be found in Table S3 and S4. We didn't find any electrode that was conflict-selective for all the three tasks in all the frequency bands we analyzed.

Figure S7



Figure S7. Example conflict modulated responses showing correlation with reaction time. The plots show the mean high-gamma power (z-scored) in each trial as a function of the reaction time for 3 example electrodes during the (**A**) Stroop (left rostral middle frontal cortex), (**B**) Flanker (right superior frontal cortex)), and (**C**) Number task (right inferior temporal cortex). Each point shows one trial. The number of trials is shown in each subplot. Electrode locations are shown on the right. The solid lines show the linear fits. Correlations were statistically significant for incongruent trials (right) but not congruent trials (left) (see p values in legend).



Figure S8. Example electrodes showing conflict modulation in two tasks. A. An electrode located in the left inferior parietal lobule (see location on the right) exhibited conflict modulation in the Stroop and Flanker tasks but not in the Number task. Traces show z-scored high gamma power (mean±SEM, black for congruent and red for incongruent) aligned to behavioral response time. Vertical dashed lines denote the average stimulus onsets. Yellow background indicates statistically significant power difference between congruent and incongruent trials (permutation test, 5,000 iterations, α =0.05, Methods). Legend shows the number of congruent (C) and incongruent (I) trials. **B**. An electrode located at the right supramarginal exhibited conflict modulation in the Stroop and Number tasks but not in the Flanker task. **C**. An electrode located in the right insula exhibited conflict modulation in the Stroop task. Brain was rendered transparent for better visualization of that electrode in deep structures.



Figure S9. Example dual-task electrodes. Stimulus aligned responses for the electrodes in Figure S8.



Figure S10. One of two task invariant electrodes. Using global referencing instead of bipolar referencing, a shorter duration threshold, and less stringent test (t-test) to distinguish incongruent and congruent trials (50 ms instead of 150 ms), we found two electrodes out of 748 electrodes (0.3%) that showed task invariance, one of them is shown here. Yellow bars indicate significant windows. This electrode was located in the left superior frontal gyrus.



Figure S11. Task-specificity in population-based decoding of conflict in single trials. Cross-task training and testing using high-gamma (**A**) or theta (**B**) band power. This figure follows the same format as **Figure 7B, D** in the main text. In contrast to **Figure 7**, here we used all conflict-selective electrodes (high-gamma: N(Stroop)=42, N(Flanker)=49, N(Number)= 59; theta: N(Stroop)=32, N(Flanker)=38, N(Number)=56), including both taskspecific and dual-task ones. The SVM classifier was trained on one task and tested on the other two tasks. The diagonal corresponds to training and testing within the same task and the off-diagonal entries show cross-task extrapolation. P values indicate the comparison between within-task and cross-task testing performances in each electrode population (permutation test with 10,000 iterations, one-sided). Accuracy is reflected by the color of each square (see color map on the right).



Figure S12. PFC population-based decoding of conflict in single trials. A, **C**. Accuracy of SVM classifier in congruent/incongruent discrimination when using a population of *all* n=188 electrodes in the prefrontal cortex. This figure follows the format in **Figure 7A,C**. In contrast to **Figure 7**, here we use the same electrode population for all three tasks and that is why there are only 3 bars here, as opposed to the 9 bars in **Figure 7**. The SVM classifier was trained and tested with ten-fold cross-validation x 50 sessions of random sampling of trials using the high-gamma (**A**) or theta (**C**) band power data from the Stroop (red), Flanker (yellow), or Number (blue) tasks. Asterisks indicate that performance was significantly higher than chance (permutation test, 10,000 iterations, one-sided, p<0.001, $\alpha=0.05$). **B**, **D**. Cross-task training and testing using high-gamma (**B**) or theta (**D**) band power. Here we used the same population from parts **A** and **C**. The SVM classifier was trained on one task and the off-diagonal entries show cross-task extrapolation. P values indicate the comparison between within-task and cross-task testing performances in each electrode population (permutation test with 10,000 iterations, one-sided). Accuracy is reflected by the color of each square (see color map on the right).

Table S1: Subject information. Information about each participant and the number of blocks completed. Bolded entries indicate subjects who performed fewer or more than the default target number of blocks, which is 6 blocks for each task.

Subject Number	Age	Gender	Hospital	Number of blocks (Stroop, Flanker, Number)	Number of electrodes
1	13	male	BCH	6, 6, 6	145
2	12	female	BCH	6, 6, 6	168
3	14	female	BCH	6, 6, 6	194
4	13	male	BCH	3, 3, 3	215
5	41	female	BWH	7, 7, 5	72
6	58	female	BWH	6, 6, 6	119
7	62	male	JHMH	7, 6, 6	99
8	41	male	JHMH	6, 6, 6	48
9	26	male	TVGH	6, 6, 6	92
10	27	female	TVGH	6, 6, 6	104
11	29	female	TVGH	6, 6, 6	101
12	29	male	TVGH	6, 6, 6	126
13	25	male	TVGH	6, 6, 6	102
14	20	female	TVGH	6, 6, 4	98
15	12	female	TVGH	6, 6, 6	90
16	24	male	TVGH	6, 6, 6	104

Table S2: Distribution of electrode locations. Number of electrodes in each location. Left and right hemispheres were combined.

Location	Count
'Left-Amygdala'	16
'Left-Hippocampus'	16
'Left-Putamen'	9
'Right-Amygdala'	12
'Right-Hippocampus'	11
'ctx-lh-bankssts'	2
'ctx-lh-caudalanteriorcingulate'	2
'ctx-lh-caudalmiddlefrontal'	1
'ctx-lh-fusiform'	5
'ctx-lh-inferiorparietal'	22
'ctx-lh-inferiortemporal'	10
'ctx-lh-insula'	14
'ctx-lh-lateraloccipital'	1
'ctx-lh-lateralorbitofrontal'	14
'ctx-lh-lingual'	3
'ctx-lh-medialorbitofrontal'	6
'ctx-lh-middletemporal'	15
'ctx-lh-parahippocampal'	4
'ctx-lh-parsopercularis'	3
'ctx-lh-parsorbitalis'	1
'ctx-lh-parstriangularis'	8
'ctx-lh-postcentral'	2
'ctx-lh-posteriorcingulate'	2
'ctx-lh-precentral'	1
'ctx-lh-rostralanteriorcingulate'	3
'ctx-lh-rostralmiddlefrontal'	30
'ctx-lh-superiorfrontal'	15
'ctx-lh-superiorparietal'	4
'ctx-lh-superiortemporal'	14
'ctx-lh-supramarginal'	6
'ctx-rh-bankssts'	5
'ctx-rh-caudalanteriorcingulate'	3
'ctx-rh-caudalmiddlefrontal'	22
'ctx-rh-cuneus'	3
'ctx-rh-entorhinal'	1
'ctx-rh-frontalpole'	1
'ctx-rh-fusiform'	19
'ctx-rh-inferiorparietal'	21

'ctx-rh-inferiortemporal'	18
'ctx-rh-insula'	27
'ctx-rh-isthmuscingulate'	8
'ctx-rh-lateraloccipital'	7
'ctx-rh-lateralorbitofrontal'	11
'ctx-rh-lingual'	7
'ctx-rh-medialorbitofrontal'	5
'ctx-rh-middletemporal'	23
'ctx-rh-paracentral'	9
'ctx-rh-parahippocampal'	6
'ctx-rh-parsopercularis'	9
'ctx-rh-parsorbitalis'	3
'ctx-rh-parstriangularis'	5
'ctx-rh-pericalcarine'	6
'ctx-rh-postcentral'	29
'ctx-rh-posteriorcingulate'	8
'ctx-rh-precentral'	43
'ctx-rh-precuneus'	13
'ctx-rh-rostralanteriorcingulate'	3
'ctx-rh-rostralmiddlefrontal'	15
'ctx-rh-superiorfrontal'	26
'ctx-rh-superiorparietal'	33
'ctx-rh-superiortemporal'	21
'ctx-rh-supramarginal'	29
'ctx-rh-temporalpole'	1
'ctx-rh-transversetemporal'	2
Total	694

Table 3. Location and specificity of conflict-modulated electrodes (high-gamma band). For each location, the table reports the number of electrodes that show conflict modulation in one task only, in two tasks, or in all three tasks. S=Stroop, F=Flanker, N=Number.

Location	One task	only		Two tasks			All	Sum
	Stroop	Flanker	Number	S+F	S+N	F+N	S+F+N	
Amygdala		1	1					2
ctx-caudalmiddlefrontal	1	1						2
ctx-entorhinal			1					1
ctx-fusiform		2	4					6
ctx-inferiorparietal	3	5	2	1				11
ctx-inferiortemporal		2	6			1		9
ctx-insula	1	3	3			2		9
ctx-lateraloccipital			3					3
ctx-lateralorbitofrontal	4	2						6
ctx-middletemporal	2	1	1					4
ctx-paracentral	1							1
ctx-parahippocampal	1		1					2
ctx-parstriangularis		1				1		2
ctx-pericalcarine			1					1
ctx-postcentral	2		2					4
ctx-posteriorcingulate		1	1					2
ctx-precentral	4	5	1			1		11
ctx-precuneus			2					2
ctx- rostralanteriorcingulate			1					1
ctx-rostralmiddlefrontal	6	2			2			10
ctx-superiorfrontal	3	5	1		1	4		14
ctx-superiorparietal	1	2	10			2		15
ctx-superiortemporal	1	1						2
ctx-supramarginal	4	3	2		1			10
Hippocampus	1		1					2
Putamen	2							2
Total	37	37	44	1	4	11	0	134
	118			16			0	134

Table 4. Location and specificity of conflict-modulated electrodes (theta band). For each location, the table reports the number of electrodes that show conflict modulation in one task only, in two tasks, or in all three tasks. S=Stroop, F=Flanker, N=Number.

Location	One task only		Two tasks			All	Sum	
	Stroop	Flanker	Number	S+F	S+N	F+N	S+F+N	
Amygdala	1							1
ctx-bankssts			1					1
ctx-caudalmiddlefrontal	1	3	1					5
ctx-cuneus			1					1
ctx-fusiform	1	1	5		1	1		9
ctx-inferiorparietal		3	3	1				7
ctx-inferiortemporal		2	5			1		8
ctx-insula	1	2	1					4
ctx-isthmuscingulate	1	1		1				3
ctx-lateraloccipital			4	1	2			7
ctx-lateralorbitofrontal	1			1				2
ctx-lingual		1	2	1	1			5
ctx-medialorbitofrontal		1	1					2
ctx-middletemporal		1	1					2
ctx-parahippocampal		1	1					2
ctx-parsopercularis		1	2					3
ctx-parstriangularis	2		1					3
ctx-pericalcarine	2							2
ctx-postcentral	1	1						2
ctx-precentral		3						3
ctx-precuneus	1		1		1			3
ctx-rostralmiddlefrontal		2	3					5
ctx-superiorparietal		4	7		5			16
ctx-superiortemporal	2	1	1					4
ctx-supramarginal	2	2						4
Hippocampus	1	1						2
Putamen			3					3
Total	17	31	44	5	10	2	0	109
	92			17			0	109

Subject	One task only			T	Two tasks		Two tasks			Sum	Sum(percentage)
	Stroop	Flanker	Number	S+F	S+N	F+N	S+F+N				
Sub1	4	1	1		2	1		9	6.21%		
Sub2		1	22			6		29	13.69%		
Sub3	1	8	7			1		17	8.76%		
Sub4	6	9	1					16	7.44%		
Sub5	2				2			4	5.55%		
Sub6	4	1	2			1		8	6.72%		
Sub7	2	1	1					4	4.04%		
Sub8		1						1	2.08%		
Sub9								0	0		
Sub10	5	5	3					13	12.50%		
Sub11	5	3						8	7.92%		
Sub12		1	3					4	3.17%		
Sub13	3		1	1				5	4.90%		
Sub14	1	2						3	3.06%		
Sub15	4	2				1		7	7.78%		
Sub16		2	3			1		6	5.77%		
Total	37	37	44	1	4	11	0	134			

Table S5: Number of conflict-selective electrodes in each subject. S: Stroop; F: Flanker; N: Number.

Table S6: Location of visually-selective electrodes. The table reports the number of electrodes that showed visual selectivity during Stroop, Flanker, and Number task respectively. Sum refers to the total number of electrodes in each location and "Total" shows the total number of electrodes in each location and "Total" shows the total number of electrodes in each task.

Location	Stroop	Flanker	Number	Sum
ctx-fusiform	2			2
ctx-inferiorparietal	1	1		2
ctx-inferiortemporal	3			3
ctx-insula	1	1		2
ctx-lateralorbitofrontal	1			1
ctx-lingual		2		2
ctx-postcentral		1		1
ctx-precuneus		1		1
ctx-rostralmiddlefrontal	2			2
ctx-superiorparietal	4	2		6
ctx-supramarginal	1			1
Total	15	8	0	23

Table S7: Location of motor-selective electrodes. The table reports the number of electrodes that showed motor selectivity for verbal and keypress responses. "Sum" refers to the total number of electrodes in each location and "Total" shows the total number of electrodes for each response modality.

Location	Verbal	Keypress	Sum
ctx-			
caudalanteriorcingulate		1	1
ctx-caudalmiddlefrontal	1		1
ctx-inferiorparietal		2	2
ctx-insula	1		1
ctx-parahippocampal		1	1
ctx-parsopercularis	1		1
ctx-parstriangularis	1		1
ctx-precentral	7	1	8
ctx-postcentral	11	2	13
ctx-superiorfrontal	1		1
ctx-superiorparietal		1	1
ctx-superiortemporal	2		2
ctx-supramarginal	1	2	3
Total	26	10	36

Frequency band	Time-bandwidth	ime-bandwidth One task only			Т	wo tas	ks	All tasks	Sum
	product, taper, moving window	S	F	N	S+F	S+N	F+N	S+F+N	
high-gamma (70-120 Hz)	5, 7 ,200 ms	37	37	44	1	4	11	0	134
low-gamma (35-70 Hz)	5, 7 ,200 ms	11	30	14	4	0	0	0	59
beta (12-35 Hz)	3, 5, 200 ms	13	26	39	0	4	1	0	83
alpha (8-12 Hz)	2, 3, 500 ms	16	40	23	1	3	7	0	90
theta (4-8 Hz)	2, 3, 500 ms	17	31	44	5	10	2	0	109

Table S8: Number of conflict-modulated electrodes considering other frequency bands