

1 **Task-specific neural processes underlying conflict resolution during cognitive control**

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15

16 **Abstract**

17 Cognitive control involves flexibly combining multiple sensory inputs with task-dependent goals
18 during decision making. Several tasks have been proposed to examine cognitive control, including
19 Stroop, Eriksen-Flanker, and the Multi-source interference task. Because these tasks have been
20 studied independently, it remains unclear whether the neural signatures of cognitive control
21 reflect abstract control mechanisms or specific combinations of sensory and behavioral aspects
22 of each task. To address this question, here we recorded invasive neurophysiological signals from
23 16 subjects and directly compared the three tasks against each other. Neural activity patterns in
24 the theta and high-gamma frequency bands differed between incongruent and congruent
25 conditions, revealing strong modulation by conflicting task demands. These neural signals were
26 specific to each task, generalizing within a task but not across tasks. These results highlight the
27 complex interplay between sensory inputs, motor outputs, and task demands and argue against
28 a universal and abstract representation of conflict.

29

30 **Introduction**

31

32 The ability to flexibly route information is central to daily activities, especially when faced
33 with a complex and conflicting interplay of sensory information, choices, and goals. Cognitive
34 control refers to the ability to regulate actions toward achieving overriding goals. Cognitive
35 control is mentally effortful because of the need to suppress autonomous responses toward
36 salient but goal-irrelevant stimulus attributes (Gratton et al., 1992; Miller and Cohen, 2001). Such
37 costs are unavoidable for successful adaptation to various environments (Diamond, 2013).
38 Impairment in cognitive control is associated with a wide range of mental disorders, including
39 addiction, depression, and schizophrenia (Goschke, 2014; Lesh et al., 2011; Zilverstand et al.,
40 2018). An essential component of cognitive control is conflict resolution, which entails mental
41 operations involving conflict detection and monitoring (Botvinick et al., 2001), response selection
42 and inhibition (Goghari and MacDonald, 2009), performance monitoring and evaluation
43 (Ridderinkhof et al., 2004), and error-detection (Fu et al., 2019; Ridderinkhof et al., 2004; Tang et
44 al., 2016).

45 Many experimental tasks have been used to study cognitive control during conflict
46 resolution. Paradigmatic examples include the Stroop task (Stroop, 1935), the Eriksen-Flanker
47 task (referred to as "Flanker" throughout the text, (Eriksen and Eriksen, 1974), and the Multi-
48 Source Interference task (MSIT, referred to as "Number" throughout the text, (Bush and Shin,
49 2006)). Common to all these tasks is the comparison between a congruent condition and an
50 incongruent condition (**Figure 1**). In the Stroop task, subjects name the font color of a color word
51 (e.g., "red," "green," "blue") when the semantic meaning of the word agrees (congruent
52 condition) or disagrees (incongruent condition) with its font color. In the Flanker task, subjects
53 have to recognize a symbol such as a letter or an arrow, embedded among the same symbols
54 (congruent condition) or different symbols (incongruent condition) (Davelaar and Stevens, 2009;
55 Eriksen and Eriksen, 1974; Mayr et al., 2003). The multi-source interference task (Bush and Shin,
56 2006) combines multiple dimensions of cognitive interference from the Stroop, Flanker, and
57 Simon (Simon and Berbaum, 1990) tasks. The MSIT stimulus consists of three numbers (chosen
58 from 0, 1, 2, or 3) in which one number (target) is always different from the other two numbers

59 (distractors). Subjects are instructed to identify the target number under conditions where it is
60 congruent (e.g., 100) or incongruent (e.g., 313) with its position.

61 The behavioral signature of this family of tasks is longer reaction time (RT) for incongruent
62 stimuli (containing conflict) compared with congruent stimuli (conflict-free). For example, in the
63 Stroop task, subjects take longer to name the font color of the word red when shown in green or
64 blue font compared to red font. The increase in reaction time during incongruent conditions is
65 due to interference from irrelevant but conflicting information and the selection among
66 competing motor plans (Goghari and MacDonald, 2009; Miller and Cohen, 2001; Stroop, 1935).

67 Multiple studies have examined brain signals associated with each one of these cognitive
68 control tasks, including measurements derived from human neuroimaging (Bunge et al., 2002;
69 Bush and Shin, 2006; Coulthard et al., 2008; Fan et al., 2003; Robertson et al., 2014; Sani et al.,
70 2021), human scalp electroencephalography (Hanslmayr et al., 2008; Janssens et al., 2018;
71 Robertson et al., 2014), human invasive neurophysiology (Caruana et al., 2014; Koga et al., 2011;
72 Oehrle et al., 2014; Sheth et al., 2012; Tang et al., 2016), and monkey neurophysiology (Blackman
73 et al., 2016; Cole et al., 2009; Li et al., 2019; Nakamura et al., 2005). These studies have described
74 an extensive network of frontal and parietal regions, and to a lesser extent temporal and other
75 regions, that demonstrate distinct activation patterns between congruent and incongruent trials.

76 The neural differences between incongruent and congruent trials reported in those
77 studies are often interpreted to reflect a correlate of a general and abstract notion of conflict
78 irrespective of the specific combination of shapes, colors, input modalities, and behavioral
79 outputs in any particular task. Thus, theories of cognitive flexibility refer to processes like error
80 monitoring and conflict resolution which are thought to be independent of the specific sensory
81 inputs that lead to such errors or conflict and which are also considered to be independent of the
82 specific motor outputs involved in a particular task. For example, the conflict monitoring theory
83 (Botvinick et al., 2001) expresses an abstract, domain-general notion of conflict: if certain
84 neurons can detect the occurrence of conflict, these neurons should be activated regardless of
85 the task implementation format. Such an abstract notion of conflict is also used in the
86 interpretation of the Gratton effect, which describes the history-dependence of conflict
87 modulation (Gratton et al., 1992; Sheth et al., 2012).

88 Combining these empirical and theoretical ideas, here we evaluate whether there are
89 shared mechanisms involved in error monitoring and conflict resolution that are common across
90 different sensory inputs and motor outputs. We focus on how conflict is represented in the brain
91 by directly comparing neurophysiological responses during three cognitive control tasks,
92 analyzing intracranial field potentials from 694 electrodes implanted in patients with
93 pharmacologically intractable epilepsy. We hypothesize that conflict-related responses should
94 show invariance to the stimulus properties within each task (within-task invariance). For example,
95 in the Stroop task, we would expect that neural responses would distinguish congruent (RED/red,
96 GREEN/green, or BLUE/blue) from incongruent (RED/green, RED/blue, GREEN/red, GREEN/blue,
97 BLUE/red, or BLUE/green) conditions, irrespective of the specific font/semantic combination.
98 Extending this hypothesis of within-task invariance to the comparisons across tasks, the
99 assumption of an abstract notion of conflict led to our second hypothesis, that neural responses
100 would distinguish conflict irrespective of whether incongruency is dictated by color, shape, or
101 number stimuli, and also regardless of the specific motor outputs involved (across-task
102 invariance). The results are consistent with the first hypothesis; neural signals that show
103 modulation between incongruent and congruent trials are invariant to stimulus attributes within
104 a task. In contrast, our results are inconsistent with the second hypothesis. The majority of the
105 neural responses demonstrate robust modulation between incongruent and congruent trials that
106 is task-specific and does not generalize across tasks.

107

108 **Results**

109

110 We recorded intracranial field potentials (IFPs) from 16 epilepsy patients implanted with
111 depth electrodes (**Table S1**). Subjects performed three cognitive control tasks: Stroop, Flanker,
112 and Number (**Methods, Figure 1**). Importantly, subjects performed the three tasks during the
113 same session, therefore enabling direct comparisons among the tasks. Each task began with a
114 fixation cross shown for 500 ms at the center of the screen. The Stroop task stimulus consisted
115 of color words ("RED," "GREEN," "BLUE," or the corresponding traditional Chinese characters for
116 patients in Taipei, **Methods**) shown in red, green, or blue font. Subjects were instructed to name

117 the font color (**Figure 1A**). Conflict arises when the font color does not match the meaning of the
118 word on the screen. The Flanker task stimulus consisted of five arrows in a horizontal row, and
119 subjects were asked to press the left or the right key to indicate the direction of the *center* arrow
120 (**Figure 1B**). Conflict arises when the center arrow points in the opposite direction to the other
121 four arrows. The Number task required subjects to say the *position* of the unique number ("one,"
122 "two," or "three") among three numbers shown in a horizontal row (**Figure 1C**). Conflict arises
123 when the position of the unique number does not match the actual number (e.g., number "3" in
124 position "1" in the stimulus "322"). For all the tasks, congruent and incongruent conditions, as
125 well as the stimulus dimensions (word, color, arrow direction, number identity), were randomly
126 interleaved and counterbalanced.

127

128 **Subjects showed behavioral evidence of conflict in the three tasks**

129

130 Subjects showed high accuracy in all three tasks (**Figure S1**): Stroop (congruent) = 96.8 ±
131 0.9%; Stroop (incongruent) = 90.1 ± 2.2%; Flanker (congruent) = 96.3 ± 2.8%; Flanker
132 (incongruent) = 90.2 ± 2.9%; Number (congruent) = 96.6 ± 1.7%; Number (incongruent) = 90.4 ±
133 2.3% (mean±SEM). On average, performance was significantly higher in the congruent condition
134 compared to the incongruent condition in all three tasks; this difference reached statistical
135 significance in the Stroop task ($p=0.007$, two-sided permutation test; 10,000 iterations), but not
136 in the Flanker ($p=0.33$) or Number ($p=0.39$) tasks. These observations are consistent with
137 previous work (Bush and Shin, 2006; Davelaar and Stevens, 2009; Eriksen and Eriksen, 1974;
138 MacLeod, 1991; Sheth et al., 2012; Stroop, 1935; Tang et al., 2016), and are mostly ascribed to a
139 ceiling effect (Carter and van Veen, 2007). Accuracy was high in the three tasks, with few error
140 trials to have enough power to distinguish incongruent from congruent trials statistically. We
141 focus exclusively on correct trials for the remainder of the study.

142 A hallmark of conflict in cognitive control tasks is the longer reaction time associated with
143 incongruent trials (**Figure 2A-C**). As demonstrated in previous work (Davelaar and Stevens, 2009;
144 Sheth et al., 2012; Tang et al., 2016), reaction times were longer during incongruent trials for all
145 three tasks (Stroop: $1,122\pm8$ ms vs. 953 ± 7 ms, $p<0.001$; Flanker: 875 ± 11 ms vs. 722 ± 9 ms,

146 p<0.001; Number: 1,110±8 ms vs. 972±8 ms, p<0.001; mean±SEM, two-sided permutation test,
147 10,000 iterations). The longer reaction times during incongruent trials were also statistically
148 significant at the individual subject level in the majority of cases (Stroop: 16/16 subjects; Flanker:
149 14/16 subjects; Number: 15/16 subjects). Subject number 4 showed no significant difference in
150 the Flanker and Number tasks, but this subject completed only half of a standard session.
151 Absolute reaction times differ across tasks because of the distinct response modalities (verbal or
152 keypress), because of the different number of response options (2 or 3), and because of the
153 different processing modalities (language or vision). Therefore, to assess the difficulty of each
154 task, we computed the ratio of reaction times in incongruent versus congruent trials. There was
155 no significant difference in difficulty among the three tasks (**Figure 2D**, p=0.16, non-parametric
156 one-way ANOVA). In sum, behavioral results were consistent with previous work and
157 demonstrated almost ceiling accuracy and a longer reaction time associated with incongruent
158 trials across the three tasks.

159

160 **Neural responses were modulated by conflict**

161

162 We recorded intracranial field potential activity from 1,877 electrodes (**Table S1** reports
163 the number of electrodes in each subject. We analyzed the activity from 694 bipolar-referenced
164 electrodes that were not in the white matter (**Methods**); **Figure 3** and **Table S2** report the
165 distribution of electrode locations. We focused on the neural activity in the theta band (4-8. Hz)
166 because it constitutes a key component of cognitive control (Cavanagh and Frank, 2014; Gratton
167 et al., 2018; Helfrich and Knight, 2016; Widge et al., 2019) and also on the high-gamma band (70-
168 120 Hz) given its significance in sensory, motor, control, and other cognitive functions (Crone et
169 al., 1998; Liu et al., 2009; Norman et al., 2019; Oehrni et al., 2014; Tang et al., 2016). Additional
170 results in other frequency bands (alpha, beta, low-gamma) are reported in **Table S7**. In previous
171 work (Tang et al., 2016), we reported that multiple electrodes showed activity in the high-gamma
172 band that was modulated by the presence of conflict during the Stroop task. Consistent with
173 previous work, **Figure 4** (left) depicts the high-gamma activity during the Stroop task of an
174 electrode, located in the left orbitofrontal cortex, that showed enhanced responses during

175 incongruent trials compared to congruent trials when aligning the neural signals to the behavioral
176 response. The differences between incongruent and congruent trials were highly robust and
177 could even be discerned in individual trials (compared **Figure 4C**, left versus **Figure 4B**, left).
178 Notably, the enhancement associated with conflict was also evident when the neural responses
179 were aligned to stimulus onset (**Figure 4D**, left).

180 An electrode was considered to be *conflict-modulated* if the band-filtered power during
181 incongruent conditions was significantly different from that during congruent conditions for at
182 least 150 consecutive milliseconds (permutation test, 5000 iterations, $\alpha = 0.05$) *both* when
183 responses were aligned to the behavioral response (**Figure 4A**, left) *and* also to the stimulus onset
184 (**Figure 4D**, left, **Methods**). These strict selection criteria using both alignment to behavior *and*
185 stimulus were implemented in order to exclude potential false positives. For example, signals
186 from a visually responsive electrode could be confused for conflict modulation when aligning the
187 neural responses to behavior due to the different reaction times between congruent and
188 incongruent trials (**Figure 2A-C**). An example of such a visually responsive electrode located in
189 the right lateral occipital cortex is shown in **Figure S2A-B**. Even though there seemed to be a
190 difference between incongruent and congruent conditions when neural signals were aligned to
191 the behavioral response (**Figure S2A**), this difference was absent when the neural signals were
192 aligned to the stimulus onset (**Figure S2B**). Therefore, we do not consider this type of response
193 to reveal any conflict modulation. Conversely, a motor responsive electrode could also be
194 confused for conflict modulation when aligning the neural signals to stimulus onset for the same
195 reasons (**Figure S2C-D**). Thus, the evaluation criteria for conflict modulation exclude purely
196 sensory and purely motor responses.

197 **Figure 4** showed an example electrode that revealed conflict modulation in the high-
198 gamma band during the Stroop task. Electrodes demonstrating robust conflict modulation were
199 also observed during the Flanker and Number tasks. **Figure 5A** (middle) depicts the responses of
200 an electrode in the right superior parietal that showed enhanced activity during incongruent trials
201 in the Flanker task. As described for the Stroop task, conflict modulation was observed in single
202 trials (**Figure S3A**, middle) and also when aligning the responses to stimulus onset (**Figure S3B**,
203 middle). **Figure 5B** (right) depicts the responses of an electrode in the right precuneus that

204 showed enhanced activity during incongruent trials in the Number task. **Figure S4A** (right) shows
205 conflict modulation for this electrode during single trials and **Figure S4B** confirmed this conflict
206 modulation even when aligning neural activity to the stimulus onset.

207 Similar results were observed when considering the theta frequency band. **Figure 6** shows
208 an example electrode in the right precentral cortex that demonstrated conflict modulation in the
209 theta frequency band during the Flanker task. Such modulation can be appreciated both in
210 response-aligned signals (**Figure 6A**) and stimulus-aligned signals (**Figure 6D**) signals, as well as in
211 individual trials (**Figure 6B-C**). **Figures 5C** and **5D** show example electrodes, in the right pars
212 triangularis and left superior temporal cortex, that exhibited conflict modulation in the theta
213 band for the Stroop and Number tasks, respectively. **Figures S5** and **S6** show responses in
214 individual trials and stimulus-aligned signals for these two example electrodes.

215 Out of the total of 694 electrodes, we identified 134 electrodes (19%) that exhibited
216 conflict modulation in at least one task in the high-gamma band (**Table S3**) and 109 electrodes
217 (16%) when considering the theta band (**Table S4**). In most cases, conflict modulation was
218 characterized by enhanced high-gamma-band power in the incongruent condition compared to
219 the congruent condition, as illustrated in the three example electrodes shown in **Figure 4-6**. A
220 few electrodes exhibited the reverse modulation direction where the congruent response was
221 higher than the incongruent one (**Figure S11A**, middle). **Figure S7** shows the distribution of
222 locations of electrodes revealing conflict modulation for each task. In sum, using strict criteria,
223 we found electrodes that demonstrate robust conflict modulation in each of the three tasks,
224 considering both high-gamma and theta band signals, evident in both behavior- and stimulus-
225 aligned responses, and even in single trials.

226

227 **Neural signals in the high-gamma band during incongruent trials correlated with reaction times**

228

229 Next we examined whether the neural signals were correlated with behavior. For each of
230 the conflict-modulated electrodes, we plotted the mean high-gamma band power as a function
231 of the reaction time (**Methods**). **Figure 7A** shows an example electrode located in the left rostral
232 middle frontal cortex that was modulated by conflict during the Stroop task. The mean high-

233 gamma power was not correlated with reaction times during congruent trials (**Figure 7A**, left,
234 p=0.3), but there was a significant correlation during incongruent trials (**Figure 7A**, right, p=0.03).
235 Similarly, **Figure 7B** shows an example electrode in the right superior frontal cortex that showed
236 a correlation with reaction times during the Flanker task and **Figure 7C** shows an example
237 electrode in the right inferior temporal cortex that showed a correlation with reaction times
238 during the Number task. In all, 8.3%, 12.2%, and 10.2% of the conflict modulated electrodes
239 showed a correlation with reaction time during incongruent trials, but not congruent trials, for
240 the Stroop, Number, and Flanker tasks, respectively.

241 These observations did not extend to the theta band. Signals in the theta band showed a
242 much weaker correlation with reaction times. We found only 4 conflict-modulated electrodes, 2
243 in the Flanker task, 2 in the Number task, and none in the Stroop task, that demonstrated a
244 statistically significant correlation between theta band power and reaction times.

245

246 **Conflict representation exhibited within-task invariance**

247

248 In each task, there are different stimuli that define conflict. For example, in the Stroop
249 task, there are six different word/color combinations that are incongruent and three that are
250 congruent (**Figure S8**). Our first hypothesis states that conflict modulation is *invariant* to the
251 different stimuli defining incongruence within a task. To test this hypothesis, we evaluated
252 whether the modulation of neural signals underlying conflict was evident only for certain stimuli
253 defining incongruent trials but *not* other stimuli within each task, as opposed to a uniform
254 modulation due to incongruent trials across the different stimuli within each task.

255 One might expect stimulus specificity given the extensive documentation of selective
256 responses to different sensory inputs (e.g., (Liu et al., 2009), among many others). For example,
257 an electrode located in visual cortical area V4 might be selective for color and respond
258 differentially to RED compared to BLUE or GREEN. Indeed, consistently with previous work, we
259 found multiple visually selective electrodes (Stroop: 15 electrodes; Flanker: 8 electrodes; Number:
260 0 electrodes; Total = 23 electrodes; **Methods, Table S5**). Similarly, we found 36 motor selective
261 electrodes (Verbal response: 26 electrodes; Keypress response: 10 electrodes; Total = 36

262 electrodes; **Methods, Table S6**). Among these 23+36=59 electrodes, there were only 5 electrodes
263 (3 visually-selective electrodes and 2 motor-selective electrodes and) that showed visual or
264 motor selectivity *and* conflict modulation in the same task. These 5 electrodes constitute 8% of
265 the visual/motor selective electrodes and 4% of all the electrodes that showed conflict
266 modulation. Thus, the majority of electrodes that showed conflict modulation were *not* visually
267 or motor selective.

268 To further investigate whether conflict modulation generalized across the different
269 sensory inputs, we directly compared the responses to all possible stimuli within each task. **Figure**
270 **S8A-I** describes the responses of an electrode in the left inferior parietal cortex for every
271 word/color combination during the Stroop task. Conflict modulation cannot be ascribed to
272 responses to specific word/color combinations; that is, conflict modulation showed *within-task*
273 *invariance* with enhanced responses during incongruent trials for the six different possible
274 incongruent word and font color combinations compared to the three different possible
275 congruent word and font color combinations. An example in the theta band is shown in **Figure**
276 **S8J-R**. Similarly, **Figure S9A-D** describes the responses of an electrode in the left orbitofrontal
277 gyrus for every combination of central and peripheral arrow directions during the Flanker task.
278 Conflict modulation in the Flanker task was also invariant within the task; that is, there was higher
279 activity during both incongruent target/flanker combinations compared to the two congruent
280 combinations. An example in the theta band is shown in **Figure S9E-H**. **Figure S10A-F** describes
281 the responses of an electrode in the left superior frontal gyrus, showing that conflict modulation
282 was evident for all the different incongruent conditions in the Number task. An example in the
283 theta band is shown in **Figure S10G-L**.

284 To characterize the degree of within-task invariance at the electrode ensemble level, we
285 used a machine learning decoding approach to assess whether we could decode the presence of
286 conflict in individual trials (**Figure 8**). In all the decoding analyses, an SVM classifier with a linear
287 kernel was trained after concatenating all the conflict modulated electrodes in each task. We
288 used two neural features: the maximum and the mean band power during each trial (**Methods**),
289 either for the high-gamma band (**Figure 8A**) or the theta band (**Figure 8B**). In all cases, we used
290 cross-validation, separating the data into a training set and an independent test set and we

291 randomly subsampled the data to ensure that the number of congruent trials matched the
292 number of incongruent trials. To evaluate within-task invariance, the classifier was trained using
293 only a subset of the different stimulus combinations and tested on different stimulus
294 combinations. For example, in the first bars in **Figure 8A** and **8B**, the SVM classifier was trained
295 with the neural responses to GREEN/red, GREEN/blue, BLUE/red, BLUE/green, GREEN/green, and
296 BLUE/blue. The classifier's performance was tested using the remaining conditions: RED/green,
297 RED/blue, and RED/red. Even though the classifier was never exposed to the neural responses to
298 any stimulus with the word "RED" during training, the classifier could extrapolate to identify
299 conflict with those novel stimuli in the same task. Similar conclusions were reached for the other
300 possible combinations of training and test stimuli within the Stroop task (**Figure 8**, red bars) and
301 also for the different combinations in the Flanker (yellow bars) and Number (blue bars) tasks. In
302 sum, both at the individual electrode level (**Figures S8-S10**) as well as at the electrode population
303 level (**Figure 8**), and both in the high-gamma (**Figure 8A**) and theta band (**Figure 8B**), the results
304 support the hypothesis that the neural signals modulated by conflict are largely independent of
305 the specific combination of stimuli that give rise to incongruence *within* each task.
306

307 **Conflict-modulated electrodes were task-specific**

308
309 Given the extrapolation across stimuli within a task, we next considered the hypothesis
310 that neural signals representing conflict would also be independent of the specific sensory and
311 motor characteristics of the task. We asked whether electrodes showing conflict modulation
312 were *task-specific* (i.e., showing activity modulation during incongruent trials in *some* but not all
313 tasks) or task-invariant (i.e., showing activity modulation during incongruent trials in *all* three
314 tasks). The examples in **Figures 4-6** illustrate example electrodes with high specificity in their
315 degree of conflict modulation. The electrodes in **Figure 4** and **Figure 5C** only revealed conflict
316 modulation during the Stroop task (compare leftmost column to middle and rightmost columns).
317 Similarly, the electrodes in **Figure 5A** and **Figure 6** showed conflict modulation only during the
318 Flanker task (middle column), and the electrodes in **Figure 5B** and **Figure 5D** only during the
319 Number task (rightmost column). These types of neural responses were representative of the

320 majority of the data. Out of the total of 134 electrodes that showed conflict modulation in the
321 high-gamma band, 118 electrodes (88%) exhibited modulation in one task but not in the other
322 two tasks. Similarly, out of the total of 109 electrodes that showed conflict modulation in the
323 theta band, 92 electrodes (84%) exhibited modulation in one task but not in the other two tasks.

324 Although most electrodes demonstrated conflict modulation in one task only, there were
325 16 electrodes in the high-gamma band (12%) and 17 electrodes (16%) in the theta band that
326 showed conflict modulation in two tasks. Three examples of electrodes that showed conflict
327 modulation in two tasks are illustrated in **Figures S11-S12**. In **Figure S11A**, an electrode in the left
328 inferior parietal cortex exhibited conflict modulation during the Stroop and Flanker tasks, but not
329 during the Number task. Similarly, **Figure S11B** shows an electrode at the right supramarginal
330 gyrus, demonstrating conflict modulation in the Stroop and Number tasks, but not during the
331 Flanker task. **Figure S11C** shows an electrode in the insula exhibiting conflict modulation during
332 the Flanker and Number tasks, but not during the Stroop task. These electrodes also showed
333 conflict modulation when the neural signals were aligned to stimulus onset (**Figure S12**). **Table**
334 **S3** and **Table S4** report the locations and task specificity for all the dual-task modulated
335 electrodes for the high-gamma and theta band, respectively.

336 In sum, most electrodes demonstrated conflict modulation in one task and few electrodes
337 showed conflict modulation in two tasks. Remarkably, we did not find *any* electrodes that were
338 modulated by conflict in all three tasks. Given the complete absence of any task-invariant
339 electrodes, we asked whether it is possible that we missed indications of invariance due to our
340 stringent criteria. First, we considered whether it is possible that having elevated activity in the
341 congruent condition could be a prerequisite to observe conflict modulation. The electrode in
342 **Figure 4** showed conflict modulation for the Stroop task but not in the other two tasks. During
343 the Flanker task, this electrode showed no elevated response whatsoever, and during the
344 Number task, there was a high response with respect to baseline starting about 0.7 seconds
345 before the behavioral response, but this increase was very much the same for congruent and
346 incongruent trials. Thus, there can be activation in the congruent condition without conflict
347 modulation. Similarly, in the example electrode in **Figure 5B**, there was an elevated response in
348 the congruent condition during all three tasks. However, conflict modulation occurred only in the

349 Number task. In total, 302 electrodes showed elevated high-gamma band responses during the
350 congruent condition in at least one task. Among these electrodes, only 80 (26%) also showed
351 conflict modulation. Moreover, the majority of these electrodes (70 out of 80) did not share the
352 same task specificity, i.e., tasks showing conflict modulation did not match tasks displaying
353 responses during the congruent conditions. In sum, multiple electrodes responded during the
354 congruent condition without conflict modulation and multiple electrodes showed conflict
355 modulation only in some task(s) while still showing a response during the congruent condition in
356 other task(s). Thus, an elevated response during the congruent condition is neither necessary nor
357 sufficient to show evidence of conflict modulation. Lack of task invariance cannot be attributed
358 to lack of a response during the congruent condition.

359 Second, we asked whether lack of invariance could be attributed to the behavioral
360 performance by subjects in a given task. In an extreme hypothetical, if a subject performs the
361 Stroop task correctly and closes their eyes during the other two tasks, we might be misled into
362 thinking that an electrode showed task-specificity. Several pieces of evidence argue against this
363 possibility. First, most subjects showed high accuracy in *all* tasks, except subjects 1 and 6, who
364 performed slightly less well on the Number and Flanker task, respectively (**Figure S1**). However,
365 both subjects have electrodes that were modulated by either the Flanker or Number task, or both.
366 Second, almost all subjects showed a clear behavioral conflict effect in the three tasks (**Figure**
367 **2A-C**), except for subject 4 who performed half of the sessions and did not show behavioral
368 conflict in either the Flanker or Number task (**Figure 2B-C**). All subjects experienced conflict
369 during the Stroop task at the behavioral level (**Figure 2A**). However, electrodes like the ones
370 shown in **Figure 5ABD** and **Figure 6** clearly demonstrated no evidence of conflict modulation in
371 the Stroop task. Finally, and even more conclusively, there were many examples of different
372 electrodes in the same subject showing task-specificity for conflict modulation in *different tasks*.
373 Therefore, lack of task invariance cannot be ascribed to cases where subjects showed conflict
374 modulation in one task but not others at the behavioral level.

375 Third, the results presented thus far focus on the high-gamma and theta frequency bands.
376 Although different frequency bands of intracranial field potential signals tend to be correlated
377 (Bansal et al., 2012), it is conceivable that some of the electrodes may reveal task invariance in

378 conflict modulation in other frequency bands. To evaluate this possibility, we repeated all the
379 analyses in the following frequency bands (**Methods**): alpha (8-12 Hz), beta (12-35 Hz), and low
380 gamma (35-70 Hz). **Table S7** reports the number of electrodes that showed conflict modulation
381 for each task and for each frequency band. Summarizing **Table S7**, we found conflict modulation
382 in all frequency bands, though the total number of electrodes that showed modulation was
383 highest in the high-gamma band. Consistently with the results described in the previous sections,
384 the vast majority of electrodes revealed conflict modulation only in one task: alpha, 88%; beta,
385 94%; low-gamma, 93% (cf. 88% for the high-gamma band and 84% for the theta band). In all
386 frequency bands, we observed a small fraction of electrodes that showed conflict modulation in
387 two tasks. Importantly, we did not find any electrode that showed task-invariance in any of these
388 other frequency bands.

389 Finally, the results presented thus far relied on highly rigorous pre-processing through
390 bipolar referencing and stringent selection criteria by requiring a long window of 150 ms to
391 identify significant differences between incongruent and congruent trials and 5,000 iterations of
392 a permutation test. We relaxed all of these constraints by using global referencing, by evaluating
393 a shorter duration threshold of 50 ms, and using a t-test. We analyzed 748 electrodes (this is
394 more than the 694 electrodes reported so far because bipolar referencing reduces the number
395 of electrodes). Using these more liberal criteria, we found two electrodes in the high-gamma
396 band that showed task invariance, one located in the left superior frontal gyrus and the other
397 one in the right rostral middle frontal gyrus. One of these electrodes is shown in **Figure S13**.
398 Although the neural signals from this electrode are less compelling than the examples showing
399 task modulation in a single task or two tasks (e.g., **Figures 4-6**), these observations hint at the
400 possibility of a weaker and less localized signal common across tasks. Yet, even under these
401 liberal selection criteria, only 0.3% of the total number of electrodes that we studied
402 demonstrated task invariance in the high-gamma band and none in the other frequency bands.

403 In sum, the observations show that most of the electrodes reveal conflict modulation in
404 only one task, and few electrodes show conflict modulation in two tasks. These results lead us to
405 reject our second hypothesis of task invariance in cognitive control at the level of individual
406 electrodes.

407

408 **Electrode population level responses revealed task-specific conflict modulation in individual
409 trials**

410

411 It is conceivable that individual electrodes could show task specificity while an ensemble
412 of multiple electrodes might reflect task invariance. To evaluate this possibility, we investigated
413 whether we could decode the presence of conflict at the *electrode population level* in individual
414 trials, following the same procedure described in **Figure 8**. Depending on the specific question
415 about task-specificity, each calculation used different combinations of training and test sets, as
416 described below.

417 First, we asked whether the population of electrodes modulated by one task could classify
418 the presence of conflict on another task. In **Figure 9**, we trained nine different classifiers using
419 the high-gamma (**Figure 9A**) and theta (**Figure 9C**) band power. The first three bars used Stroop-
420 only electrodes (like the ones in **Figure 4** and **Figure 5C**), the middle three bars used Flanker-only
421 electrodes (like the ones in **Figure 5A** and **Figure 6**), and the last three bars used Number-only
422 electrodes (like the ones in **Figure 5B** and **Figure 5D**). The classifiers were trained and tested using
423 cross-validation using only responses from the Stroop task (red), using only responses from the
424 Flanker task (yellow), or using only responses from the Number task (blue). The Stroop-only
425 electrode population yielded significant classification performance when trained and tested on
426 the Stroop task (permutation test, 10,000 iterations, one-sided, $p < 0.001$, **Figure 9A** and **9C**, bar
427 1), and the Flanker-only population yielded significant classification performance when trained
428 and tested on the Flanker task ($p < 0.001$, **Figure 9A** and **9C**, bar 5). The population of Number-
429 only electrodes yielded significant classification performance when trained and tested on the
430 Number task ($p < 0.001$, **Figure 9A** and **9C**, bar 9), but also when trained and tested on the Stroop
431 task ($p < 0.01$, **Figure 9A** and **9C**, bar 7). Although the Number-only electrode population could
432 detect conflict in the Stroop task, the performance on the Number task was still significantly
433 higher than that on the Stroop task ($p < 0.001$).

434 We next sought to assess whether a classifier trained only with data from one task *could*
435 *extrapolate to detect conflict in a different task*. We trained three classifiers, one using data from

436 the Stroop task only, one using data from the Flanker task only, and one using data from the
437 Number task only using high-gamma (**Figure 9B**) and theta (**Figure 9D**) band power. Then we
438 tested each classifier with data from the Stroop, Flanker, and Number tasks, respectively. We
439 performed this analysis using Stroop-only, Flanker-only, and Number-only electrodes. Note that
440 this is different from the analyses in **Figure 9A** and **9C**, where the training and test data were
441 always from the *same task* for each classifier, whereas here, the training and test data can be
442 from different tasks. Here, even when the classifier is trained and tested using data from the
443 same task, we still performed cross-validation across trials to avoid overfitting. The results of
444 these cross-task classification analyses are presented in **Figure 9B**. As expected, the highest
445 classification accuracies were observed for *within-task training and testing* (diagonal tiles in
446 **Figure 9B** and **9D**). These three conditions not only exhibited better than chance accuracies (high-
447 gamma: $82.6 \pm 6.9\%$, theta: $79.5 \pm 8.2\%$), but also significantly higher performance than all the
448 corresponding cross-task accuracies (high-task: $55.3 \pm 4.3\%$ **Figure 9B**, $p < 0.001$; theta: $53.6 \pm 5.0\%$
449 **Figure 9D**, $p < 0.001$). In sum, even at the electrode population level, we observed minimal ability
450 to detect conflict when a decoder was trained and tested in different tasks despite the fact that
451 there was high accuracy in distinguishing conflict in individual trials within each task.
452

453 Discussion

454

455 We studied the neural mechanisms underlying conflict resolution during cognitive control
456 by recording intracranial field potentials from 694 electrodes in 16 subjects who performed three
457 different tasks: Stroop, Flanker, and Number (**Figure 1**). Subjects showed increased reaction
458 times during incongruent trials compared to congruent trials (**Figure 2**), a hallmark of cognitive
459 control (Bush and Shin, 2006; Eriksen and Eriksen, 1974; Mayr et al., 2003; Stroop, 1935).
460 Consistent with previous studies (Caruana et al., 2014; Gaetz et al., 2013; Koga et al., 2011; Tang
461 et al., 2016), we found robust modulation of neural signals in the high-gamma frequency band
462 when comparing incongruent versus congruent trials (**Figures 4, 5**). Conflict modulation was also
463 present in the theta band (**Figures 5, 6**) and other frequency bands (**Table S7**). Modulation was
464 evident both when aligning neural signals to the behavioral responses and to stimulus onset

465 (**Figures 4, 6, S3-6, S12**), could be appreciated even in single trials (**Figures 4, 6, Figures S3-S6**),
466 and showed *within-task invariance* to the different combinations of visual inputs (**Figures 8, S8-**
467 **S10**). Surprisingly, despite this robust within-task invariance, most of the electrodes showed *task-*
468 *specificity*, with clear incongruent/congruent modulation in only one task but not in the other
469 two (**Figure 4-6**). A few electrodes showed task-modulation in two tasks but not the third task
470 (**Figure S11**).

471 We were concerned about multiple potential factors that could masquerade as task
472 specificity. First, if subjects failed to perform a given task adequately or failed to show conflict at
473 the behavioral level in a given task, one may wrongly conclude that there is task specificity in the
474 neural responses. However, all subjects revealed high accuracy in the three tasks (**Figure S1**), and
475 the vast majority of subjects showed conflict at the behavioral level (**Figure 2A-C**). We observed
476 task-specificity in the neural signals even in subjects that showed conflict at the behavioral level
477 in all three tasks. Furthermore, there were electrodes in the same subject with different task-
478 specificity, ruling out an explanation of task-specificity based on poor behavior. Another potential
479 behavioral factor that could correlate with task-specificity would be if one task showed more
480 "conflict" than the other tasks. However, the reaction times showed that the three tasks were
481 comparable in terms of their degree of behavioral conflict (**Figure 2D**). Additionally, if there were
482 a gradient of "conflict," say Stroop > Flanker > Number, one may expect to observe task-
483 specificity only for Stroop, followed by electrodes that show modulation in both Stroop and
484 Flanker, followed by electrodes that show invariance to all three tasks. However, this possibility
485 does not match our observations since we report task-specific electrodes for each of the three
486 tasks.

487 We used stringent criteria to ascribe conflict modulation to an electrode (**Methods**). We
488 considered whether it is possible that task-specificity could be dictated by a lack of response
489 during congruent trials, but this was not the case. We showed that an elevated response during
490 the congruent condition was neither necessary nor sufficient to show evidence of conflict
491 modulation. We also considered whether our strict selection criteria could have biased the
492 interpretation of our results. However, an inspection of the individual trials reveals robust
493 modulation during incongruent trials compared to congruent trials in some tasks but not others

494 (**Figures 4, 6, S3-6**). Even after relaxing pre-processing by using a global reference and a much
495 less stringent statistical threshold, only two electrodes (less than 1%) revealed task invariance.
496 Similar conclusions were reached when examining other frequency bands (**Table S7**).

497 We also considered an electrode ensemble machine learning decoding approach (**Figures**
498 **8-9**). Population-based decoding is highly sensitive and could, in principle, uncover a task-
499 invariant representation even if we mainly observe specificity in individual trials and individual
500 electrodes. However, the decoding results also support the conclusion of clear within-task
501 invariance (**Figure 8**) and a largely task-specific representation (**Figure 9**). These decoding results
502 cannot be ascribed to drifting neural signals or non-stationarities in the data. First, previous work
503 showed that intracranial field potentials tend to be very stable within a session, and even across
504 recording sessions spanning multiple days (Bansal et al, 2012). Second and most importantly, the
505 total of 18 blocks with different tasks were randomly interleaved and the signals were still more
506 consistent within a task than across tasks.

507 It is important to emphasize that our sampling of brain locations is extensive but certainly
508 not exhaustive (**Figure 3**). Therefore, it is quite possible that there are other brain regions that
509 represent conflict in a task-invariant fashion in areas that we could not sample here. It is also
510 relevant to highlight that our study focuses on intracranial field potentials; these signals combine
511 the activity of large numbers of neurons. It is conceivable that individual neurons might show
512 more, or less, task invariance than the results reported here. However, recent studies examining
513 single unit activity in the frontal cortex are also consistent with a lack of task-invariance in
514 cognitive control (Ebitz et al., 2020; Fu et al., 2019; Smith et al., 2019). Several studies have shown
515 that frontal cortex neurons demonstrate “mixed selectivity” (Rigotti et al., 2013). Such mixed
516 selectivity is a good summary of the results described here at the level of intracranial field
517 potentials, which seem to reflect a combination of conflict and task-specific demands.

518 These task-specific electrodes were located in multiple regions within the frontal, parietal,
519 and temporal lobes, and to a lesser degree, the occipital lobe. Several studies documented
520 differential activation during incongruent versus congruent trials in the frontal cortex (Bunge et
521 al., 2002; Caruana et al., 2014; Fan et al., 2003; Milham and Banich, 2005; Parris et al., 2019;
522 Robertson et al., 2014; Sheth et al., 2012; Tang et al., 2016). The locations shown in **Figure S7** and

523 **Table S3-4** are also consistent with many studies documenting responses during cognitive control
524 in the parietal cortex (Bunge et al., 2002; Bush and Shin, 2006; Coulthard et al., 2008; Fan et al.,
525 2003), temporal cortex (Bush and Shin, 2006; Fan et al., 2003), occipital cortex (Egner and Hirsch,
526 2005; Fan et al., 2003; Janssens et al., 2018), and other brain areas such as the insula (Menon
527 and Uddin, 2010). These results suggest that cognitive control processes recruit distributed and
528 task-specific networks rather than a single brain region (Dosenbach et al., 2007; Dosenbach et al.,
529 2006; Fan et al., 2003; Marek and Dosenbach, 2018).

530 Several previous studies reported signals that differ between incongruent and congruent
531 trials at the level of individual neurons (Sheth et al., 2012; Smith et al., 2019), intracranial field
532 potentials (Caruana et al., 2014; Koga et al., 2011; Oehrle et al., 2014; Tang et al., 2016), in scalp
533 electroencephalography signals (Hanslmayr et al., 2008; Janssens et al., 2018; Robertson et al.,
534 2014), and in functional neuroimaging signals (Bunge et al., 2002; Goghari and MacDonald, 2009;
535 Milham and Banich, 2005; Parris et al., 2019). These signals have been interpreted and modeled
536 as reflecting conflict (Heilbronner and Hayden, 2016; Ridderinkhof et al., 2004; Shenhav et al.,
537 2013). Multiple potential confounds could lead investigators to infer that such signals represent
538 task-invariant conflict, even though the signals only reflect task-specific differences between
539 congruent and incongruent trials. The most obvious and ubiquitous reason for this inference is
540 extrapolation based on studies that draw conclusions from a single task. With a single task, it is
541 impossible to assess task-invariance in conflict modulation. It is possible to draw inferences about
542 *potential* invariance by comparing results in different studies; however, precise anatomical
543 comparisons across subjects can be challenging, especially when considering coarse signals that
544 smooth over large numbers of neurons. Inferences across studies do not necessarily imply that
545 the same neural circuits represent conflict in an abstract format. Another potential confound is
546 the distinction between signals aligned to the stimulus or to the behavioral response, which
547 requires a careful comparison of the temporal dynamics of the neural responses. Stimulus-
548 specific neural signals could be misconstrued as conflict modulation if neural responses are
549 aligned to the motor output (e.g., **Figure S2AB**), and motor-specific neural signals could be
550 misconstrued as conflict modulation if neural responses are aligned to the stimulus onset (e.g.,

551 **Figure S2CD).** Thus, either due to single-task studies or spatial and temporal averaging, many
552 previous studies likely reflect task-specific modulation rather than an abstract conflict signal.

553

554 We deliberately designed the tasks to be different in terms of the sensory inputs and
555 motor outputs. Conflict relies on a discrepancy between color and semantic meaning (Stroop),
556 comparison between shapes (Flanker), and the meaning of numbers and positional encoding
557 (Number). Subjects used either verbal responses (Stroop, Number) or keypress responses
558 (Flanker) as output. We conjectured that a general, abstract, signature of cognitive control should
559 be independent of the inputs and outputs that define conflict. However, we found no such task-
560 invariant conflict signals. It is tempting to assume that neural signals from electrodes that show
561 conflict modulation in two tasks (e.g., **Figure S11**) correlate with the common aspects of two
562 tasks. For example, electrodes that showed modulation exclusively during the Stroop and
563 Number tasks (e.g., **Figure S11B**) might be involved in conflict expressed through verbal output.
564 However, caution should be exercised in this type of interpretation because we did not test the
565 Flanker task using a verbal output. The majority of electrodes responded in a task-specific manner,
566 arguably demonstrating engagement in conflict only through specific sensory-motor
567 combinations. Collectively, our results indicate that cognitive control is orchestrated by largely
568 distinct and distributed networks dictated by the specific demands of each task.

569

570 **Materials and Methods**

571 **Subjects and recording procedures**

572 Subjects were 16 patients (8 female, ages 12-62, **Table S1**) with pharmacologically intractable
573 epilepsy treated at Taipei Veterans General Hospital (TVGH), Boston Children's Hospital (BCH), Brigham
574 and Women's Hospital (BWH), and Johns Hopkins Medical Hospital (JHMH). The electrode locations are
575 purely dictated by clinical considerations, precluding any quantitative estimation of sample size at study
576 design. The target number of subjects, 16, was decided during study design based on historical data of
577 electrode distributions from previous studies. This study was approved by the institutional review board
578 in each hospital and was carried out with subjects' informed consent. Subjects were implanted with
579 intracranial depth electrodes (Ad-Tech, Racine, WI, USA). The electrode locations were dictated by the
580 clinical needs to localize the seizure focus in each patient (Fried et al., 2014). The total number of

581 electrodes was 1,877 (**Table S1**). Neurophysiological data were recorded using XLTEK (Oakville, ON,
582 Canada), Bio-Logic (Knoxville, TN, USA), Nihon Kohden (Tokyo, Japan), and Natus (Pleasanton, CA). The
583 sampling rate was 2048 Hz at BCH and TVGH, 1000 Hz at JHMH, and 512 Hz at BWH. All data were bipolarly
584 referenced, unless stated otherwise. There were no seizure events in any of the sessions. Electrodes in
585 the epileptogenic foci, as well as pathological areas, were removed from analyses.

586

587 **Task procedures**

588 Each subject completed three tasks in a single recording session: Stroop, Flanker, and Number. A
589 schematic rendering of the tasks is shown in **Figure 1**. Each session contained 18 blocks, with 30 trials of
590 one task (Stroop, Flanker, or Number) per block. The target number of trials was pre-defined based on
591 the results of one of our previous studies (Tang et al, 2016) and based on a pilot study with 4 healthy
592 volunteers where we confirmed that conflict (i.e., reaction time difference between congruent and
593 incongruent trials) could be robustly detected with this number of trials. Per our IRB protocols, subjects
594 can stop testing at any time; subjects who completed different numbers of blocks are indicated in **Table**
595 **S1** in bold font. Subjects completed the tasks in normally lighted and quiet rooms. The experiments were
596 written and presented using the Psychtoolbox extension in Matlab_R2016b (Mathworks, Natick, MA).
597 Subjects viewed and completed the experiment using a 13-inch Apple Mac laptop. Stimuli subtended
598 approximately 5 degrees of visual angle and were centered on the screen. Before each experiment started,
599 each subject went over a short practice session until the instructions were fully understood. During the
600 actual experiment, no correct/incorrect feedback was provided.

601 All trials started with 500 ms of fixation, followed by stimulus presentation. The stimulus was
602 presented for 2,000 ms (Stroop, Number), or until the minimum of 2,000 ms and the subject's key
603 response time (Flanker). The stimuli were presented in white (Flanker, Number) or red/green/blue font
604 color (Stroop), on a black background. For those subjects in Taipei, Stroop task stimuli were presented in
605 traditional Chinese characters. Subjects provided a verbal response recorded using a Yeti microphone with
606 an 8,192 Hz sampling rate (Stroop, Number), or a two-alternative keypress response using the left and
607 right keys on the experiment laptop (Flanker).

608

609 **Electrode localization**

610 We used the iELVis (Groppe et al., 2017) pipeline to localize the depth electrodes. Pre-implant
611 MRI (T1, no contrast) was processed and automatically segmented by Freesurfer (Dale et al., 1999; Reuter
612 et al., 2012), followed by co-registering the post-implant CT to the processed MR images. Electrodes were

613 then identified visually and marked in each subject's co-registered space using the BioImage Suite (Joshi
614 et al., 2011). Each electrode was assigned an anatomical location (parcellated cortices (Desikan et al.,
615 2006), white matter, subcortical regions, or unknown locations) using the Freesurfer localization tool.
616 Unknown locations could be due to brain lesions or pathological brain areas. Electrodes in the white
617 matter, ventricles, cerebellum, and unknown locations were excluded from analyses. Out of a total of
618 1,877 electrodes, we included 694 bipolarly referenced electrodes in the analyses. To show the position
619 of electrodes from different subjects (**Figure 3 and S7**), electrode locations were mapped onto the MNI305
620 average human brain via an affine transformation (Wu et al., 2018).

621

622 **Behavioral analyses**

623 The content of verbal responses (Stroop and Number tasks) was transcribed offline. The
624 transcription was blind to the ground truth answers as well as neural responses. The behavioral reaction
625 time for verbal response (Stroop and Number tasks) was determined as the first time the energy of the
626 soundtrack was three standard deviations above the mean energy of the whole trial. Any noise (e.g., door
627 slam, coughing, etc.) before the actual trial response was carefully identified and smoothed to prevent
628 false automatic identification of behavioral response time. The keypress reaction time (Flanker task) was
629 recorded by the Psychtoolbox code. Reaction times are shown in **Figure 2**.

630

631 **Preprocessing of intracranial field potential data**

632 A zero-phase digital notch filter (Matlab function "filtfilt") was applied to the broadband signals
633 to remove the AC line frequency at 60 Hz and harmonics. For each electrode and each task, trials with
634 amplitudes (max-min voltage from fixation onset to stimulus off) larger than three standard deviations
635 above the mean amplitude across all trials were considered as containing artifacts and excluded from
636 analysis (Bansal et al., 2012). The percentage of trials excluded by this criterion was 1.05% (Stroop), 1.25%
637 (Flanker), and 1.29% (Number).

638

639 **Single electrode analysis of modulation by conflict**

640 We computed the high-gamma band (70-120 Hz), low-gamma band (35-70 Hz), beta band (12-35
641 Hz), alpha band (8-12 Hz), and theta band (4-8 Hz) power of the intracranial field potential signals by using
642 a multi-taper moving-window spectral estimation method implemented in the Chronux toolbox (Mitra
643 and Bokil, 2008). The time-bandwidth product, number of tapers, and size of moving window used for
644 each frequency band are listed in **Table S7** (Tang et al., 2016). Throughout the paper, we focus on the

645 high-gamma band and theta band signals. The power in the corresponding frequency band was z-scored
646 by subtracting the mean high-gamma power during the baseline period (500 ms before stimulus onset)
647 and dividing by the standard deviation of the high-gamma power during the baseline. Only correct trials
648 were included in the analyses.

649 First, we examined whether an electrode exhibited any response at all to the stimuli. An electrode
650 was defined as "responsive" if the z-scored high-gamma power during the congruent condition was larger
651 than 1 for at least 150 consecutive milliseconds (15 x 200 ms window shifted by 10 ms), starting from
652 stimulus onset to average behavioral response time. To determine whether an electrode showed conflict
653 modulation (**Tables S3, S4, and S7**), we compared the band power between the congruent and
654 incongruent conditions of each task. For each time bin (200 ms shifted by 10 ms), we compared the band
655 power of incongruent versus congruent trials using a permutation test with 5,000 iterations ($\alpha = 0.05$). An
656 electrode was denoted as showing conflict modulation if the following two criteria were satisfied: (1) The
657 band power of incongruent trials was significantly different from the high-gamma power in congruent
658 trials for at least 150 consecutive milliseconds (15 x 200 ms window shifted by 10 ms); (2) Criteria (1) was
659 satisfied in both behavioral response-aligned and stimulus-aligned conditions (Tang et al., 2016). When
660 the band power was aligned to behavioral response, selection criteria were applied to the time window
661 starting from the *average stimulus onset* to the behavioral reaction time. When the band power was
662 aligned to the stimulus, the time window was from stimulus onset to *average behavioral reaction time*.

663 An electrode was considered to be visually responsive if the maximum z-scored high-gamma band
664 power was larger than 2 during the 300 milliseconds after stimulus onset. An electrode was considered
665 showing motor responsive if the maximum z-scored high-gamma band power was larger than 2 during
666 300 milliseconds before behavioral response and the power continually increased during this time window.
667 An electrode was considered to be visually selective for a particular task if it was visually responsive to
668 stimuli only in one task. An electrode was deemed to show motor selectivity if it was motor responsive to
669 verbal output (Stroop and Number) only or keypress (Flanker) only. These analyses are summarized in
670 **Tables S5 and S6**.

671 To assess the correlation between conflict responses and reaction times (**Figure 7**), a linear
672 regression ("fitlm" function in Matlab) was performed between reaction time and the mean high-gamma
673 or theta band power of each trial for all conflict-modulated electrodes. An electrode was considered to
674 show a significant correlation if the p value of the linear regression slope was smaller than 0.05.

675

676 **Classifier analyses**

677 We quantified whether we could distinguish between congruent and incongruent trials in
678 individual trials based on the activity of pseudo-populations formed by multiple electrodes (Liu et al.,
679 2009). We used a linear-kernel support vector machine with ten-fold cross-validation for all the classifier
680 analyses (**Figures 8-9**). Two features were calculated for each trial from each electrode: the mean and
681 maximum band power from average stimulus onset to the behavioral response. These analyses were
682 conducted separately for the high-gamma and theta frequency bands. All data were normalized to zero
683 mean and standard deviation 1 before each training and testing session. All the classifier performance
684 results reported are based on cross-validated test data. The main text and **Figures 8-9** describe all the
685 different combinations of training and test data used, which are critical to evaluate within-task and
686 between-task invariance.

687

688 **Data and code availability**

689 All the data and source code will be made available through public repositories upon publication.

690

691 **Author contributions**

692 The task was designed by YX and GK. All the data were collected by YX with the help of CCC, NEC,
693 IR, YCS, and DW. CRG, SS, JRM, HYY, and WSA performed the surgeries on the patients. All the
694 data were analyzed by YX, with frequent discussions with GK. The manuscript was written by YX
695 and GK and approved by all authors.

696

697 **Acknowledgments**

698 This work was supported by NIH grant R01EY026025 and by the Center for Brains, Minds and
699 Machines, funded by NSF Science and Technology Center Award CCF-1231216.

700

701 **Competing interests**

702 The authors declare no conflicts of interest.

703

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855

856 **Figure Legends**

857
858 **Figure 1. Experimental paradigms.** Subjects performed the Stroop (A), Flanker (B), and Number
859 (C) tasks in one session during intracranial neurophysiological recordings with depth electrodes.
860 A standard session contained 18 blocks and each block comprised 30 trials of each task. (A) The
861 Stroop task requires subjects to say the font color. In the congruent condition, the semantic
862 meaning coincides with the font color, while the two conflict in the incongruent condition. (B)
863 The Flanker task requires subjects to press the left or the right key to indicate the direction of the
864 central arrow. In the congruent condition, all the arrows point in the same direction while in
865 incongruent condition, the arrow in the middle points oppositely from the others (flankers). (C)
866 The Number task requires subjects to say the position ("one", "two", or "three") where the
867 unique number is located. In the congruent condition, the target number and its position are the
868 same while in the incongruent condition these are different. All trials in this figure show
869 incongruent conditions.
870

871 **Figure 2. Subjects were slower in incongruent trials in the three tasks.**

872 **A-C.** Violin plots showing distribution of reaction times for each subject for congruent trials (gray)
873 and incongruent trials (red) during the Stroop (A), Flanker (B), and Number (C) task. Only correct
874 trials are shown. Black bars indicate mean reaction time. The asterisks denote statistically
875 significant differences (two-sided permutation test, 10,000 iterations, $\alpha=0.05$).
876 **D.** There was no difference among the three tasks in task difficulty calculated as the ratio of
877 reaction times during incongruent to congruent trials (one-way ANOVA, $p=0.16$). Asterisks

878 denote significant differences in each task with respect to the null hypothesis corresponding to
879 a ratio of 1 (two-sided permutation test, 10,000 iterations, $\alpha=0.05$).
880

881 **Figure 3. Electrode locations.** Location of all n=694 electrodes overlayed on the Desikan-Killiany
882 Atlas shown with different views. **A:** Left lateral; **B:** Left medial; **C:** Superior, whole brain; **D:**
883 Inferior, whole brain; **E:** Right lateral; **F:** Right medial.
884

885 **Figure 4. Example electrode in the left orbitofrontal cortex showing conflict modulation during**
886 **the Stroop task.** **A.** The traces show the mean \pm SEM z-scored high-gamma power aligned to
887 behavioral response time for incongruent trials (red) and congruent trials (black) for each of the
888 three tasks (Column 1: Stroop; Column 2: Flanker; Column 3: Number). The vertical dashed lines
889 denote the average stimulus onset. Yellow background indicates statistically significant
890 differences between congruent and incongruent trials (permutation test, 5000 iterations, $\alpha=0.05$,
891 **Methods**). The electrode location is shown on the right. **B-C.** Raster plots showing the neural
892 signals in individual trials (see color scale on the right) for congruent (**B**) and incongruent (**C**) trials.
893 The white dashed lines in the raster plots show the average stimulus onset time. These lines are
894 shifted to the left in **C** compared to **B**, reflecting the longer reaction times during incongruent
895 trials; **Figure 2.** Gray and white bars on the left of the raster plots represent different blocks. **C.**
896 Z-scored high-gamma power (mean \pm SEM) aligned to stimulus onset. Vertical dashed lines denote
897 the average behavioral response time. Yellow background indicates statistically significant
898 difference between congruent and incongruent trials (permutation test, 5000 iterations,
899 alpha=0.05, **Methods**).
900

901 **Figure 5. Example electrode showing conflict modulation in high-gamma (A-B) and theta band**
902 **(C-D) during one task (A: Flanker; B, D: Number; C: Stroop).** The traces show mean \pm SEM z-scored
903 high-gamma (**A-B**) or theta (**C-D**) power aligned to behavioral response time for incongruent trials
904 (red) and congruent trials (black) for each of the three tasks (Column 1: Stroop; Column 2: Flanker;
905 Column 3: Number). The vertical dashed lines denote the average stimulus onset. Yellow
906 background indicates statistically significant differences between congruent and incongruent
907 trials (permutation test, 5000 iterations, $\alpha=0.05$, **Methods**). Electrode locations are shown on the
908 right (**A:** right superior parietal; **B:** right precuneus; **C:** right pars triangularis; **D:** left superior
909 temporal).
910

911 **Figure 6. Example electrode in the right precentral cortex showing conflict modulation in the**
912 **theta band during the Flanker task.** **A.** The traces show the mean \pm SEM z-scored theta power (4-
913 8 Hz) aligned to behavioral response time for incongruent trials (red) and congruent trials (black)
914 for each of the three tasks (Column 1: Stroop; Column 2: Flanker; Column 3: Number). The format
915 and conventions follow those in **Figure 4.** The vertical dashed lines denote the average stimulus
916 onset. Yellow background indicates statistically significant differences between congruent and
917 incongruent trials (permutation test, 5000 iterations, $\alpha=0.05$, **Methods**). The electrode location
918 is shown on the right. **B-C.** Raster plots showing the neural signals in individual trials (see color
919 scale on the right) for congruent (**B**) and incongruent (**C**) trials. The white dashed lines in the
920 raster plots show the average stimulus onset time. These lines are shifted to the left in **C**
921 compared to **B**, reflecting the longer reaction times during incongruent trials (**Figure 2**). Gray and
white bars on the left of the raster plots represent different blocks. **D.** Z-scored theta power

922 (mean±SEM) aligned to stimulus onset. Vertical dashed lines denote the average behavioral
923 response time. Yellow background indicates statistically significant difference between
924 congruent and incongruent trials (permutation test, 5000 iterations, alpha=0.05, Methods).
925

926 **Figure 7. Example conflict modulated responses showing correlation with reaction time.** The
927 plots show the mean high-gamma power (z-scored) in each trial as a function of the reaction time
928 for 3 example electrodes during the (A) Stroop (left rostral middle frontal cortex), (B) Flanker
929 (right superior frontal cortex)), and (C) Number task (right inferior temporal cortex). Each point
930 shows one trial. The number of trials is shown in each subplot. Electrode locations are shown on
931 the right. The solid line shows the linear fits. Correlations were statistically significant for
932 incongruent trials (right) but not congruent trials (left) (see p values in legend).
933

934 **Figure 8. Within-task invariance in population-based decoding of conflict in single trials**

935 Accuracy of support vector machine (SVM) classifier in discriminating incongruent from
936 congruent trials extrapolating across conditions within each task (within-task invariance) using
937 high-gamma (A) and theta (B) band power.

938 **Stroop task.** The first bar labeled “RED” was trained using the “GREEN” trials (as in DEF in **Figure S8**) and “BLUE” trials (as in GHI in **Figure S8**), and tested on “RED” trials (as in ABC in **Figure S8**).
939 A similar procedure was followed for the other combinations: in bar 2, the SVM was trained using
940 “RED” and “BLUE” trials, and tested on “GREEN” trials. In bar 3, the SVM was trained using “RED”
941 and “GREEN” trials, and tested on “BLUE” trials.
942

943 **Flanker task.** In the first bar, the SVM was trained on “>>>>” and “>><>>”, and tested on “<<<<<”
944 and “<><<<”. In the second bar, training and testing data were reversed.
945

946 **Number task.** In the first bar, the SVM was trained on trials where the correct answers were “two”
947 (as in CD in **FigureS10**) or “three” (as in EF in **FigureS10**), and tested on trials where the correct
948 answers were “one” (as in AB in **FigureS10**). Similarly in bar 2, the SVM was trained on “one” and
949 “three”, and tested on “two”. In bar 3, the SVM was trained on “one” and “two”, and tested on
950 trials whose target answers were “three”.
951

952 For each task, the training and testing data for each condition were randomly subsampled to
953 contain an equal number of congruent and incongruent trials. Error bars indicate s.e.m. over 50
954 sessions. The dashed line indicates chance performance (50%). Asterisks denote higher than
955 chance accuracy (permutation test with 10,000 iterations, p<0.001 for all bars).
956

957 **Figure 9. Task-specificity in population-based decoding of conflict in single trials**

958 **A, C.** Accuracy of SVM classifier in congruent/incongruent discrimination when using a population
959 of Stroop-specific electrodes (first three bars, n=37), Flanker-specific electrodes (next three bars,
960 n=37), or Number-specific electrodes (last three bars, n=44). The SVM classifier was trained and
961 tested with ten-fold cross-validation x 50 sessions of random sampling of trials using high-gamma
962 (A) and theta (C) band power from the Stroop (red), Flanker (yellow), or Number (blue) tasks.
963 Asterisks indicate that performances are significantly higher than chance (permutation test,
964 10,000 iterations, one-sided, p<0.001).
965

966 **B, D.** Cross-task training and testing. Here we used the same three populations from part A and
967 C. The SVM classifier was trained on one task and tested on the other two tasks. The diagonal
968 corresponds to training and testing within the same task and the off-diagonal entries show cross-

966 task extrapolation. P values indicate the comparison between within-task and cross-task testing
967 performances in each electrode population (permutation test with 10,000 iterations, one-sided).
968 Accuracy is reflected by the color of each square (see color map on right).
969

Figure 1

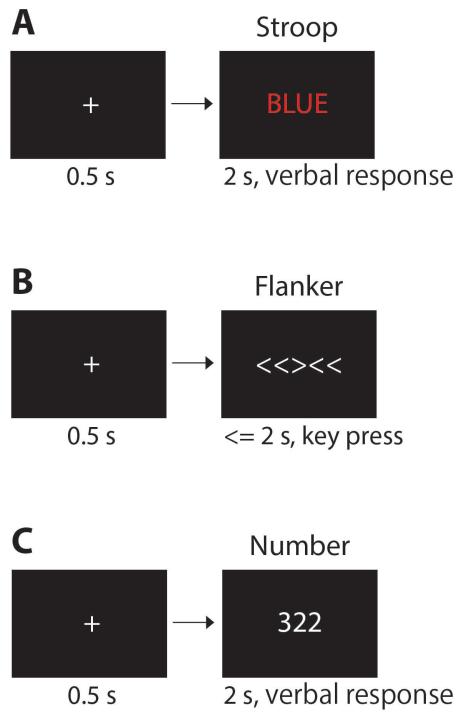


Figure 1. Experimental paradigms. Subjects performed the Stroop (**A**), Flanker (**B**), and Number (**C**) tasks in one session during intracranial neurophysiological recordings with depth electrodes. A standard session contained 18 blocks and each block comprised 30 trials of each task. (**A**) The Stroop task requires subjects to say the font color. In the congruent condition, the semantic meaning coincides with the font color, while the two conflict in the incongruent condition. (**B**) The Flanker task requires subjects to press the left or the right key to indicate the direction of the central arrow. In the congruent condition, all the arrows point in the same direction while in incongruent condition, the arrow in the middle points oppositely from the others (flankers). (**C**) The Number task requires subjects to say the position (“one”, “two”, or “three”) where the unique number is located. In the congruent condition, the target number and its position are the same while in the incongruent condition these are different. All trials in this figure show *incongruent* conditions.

Figure 2

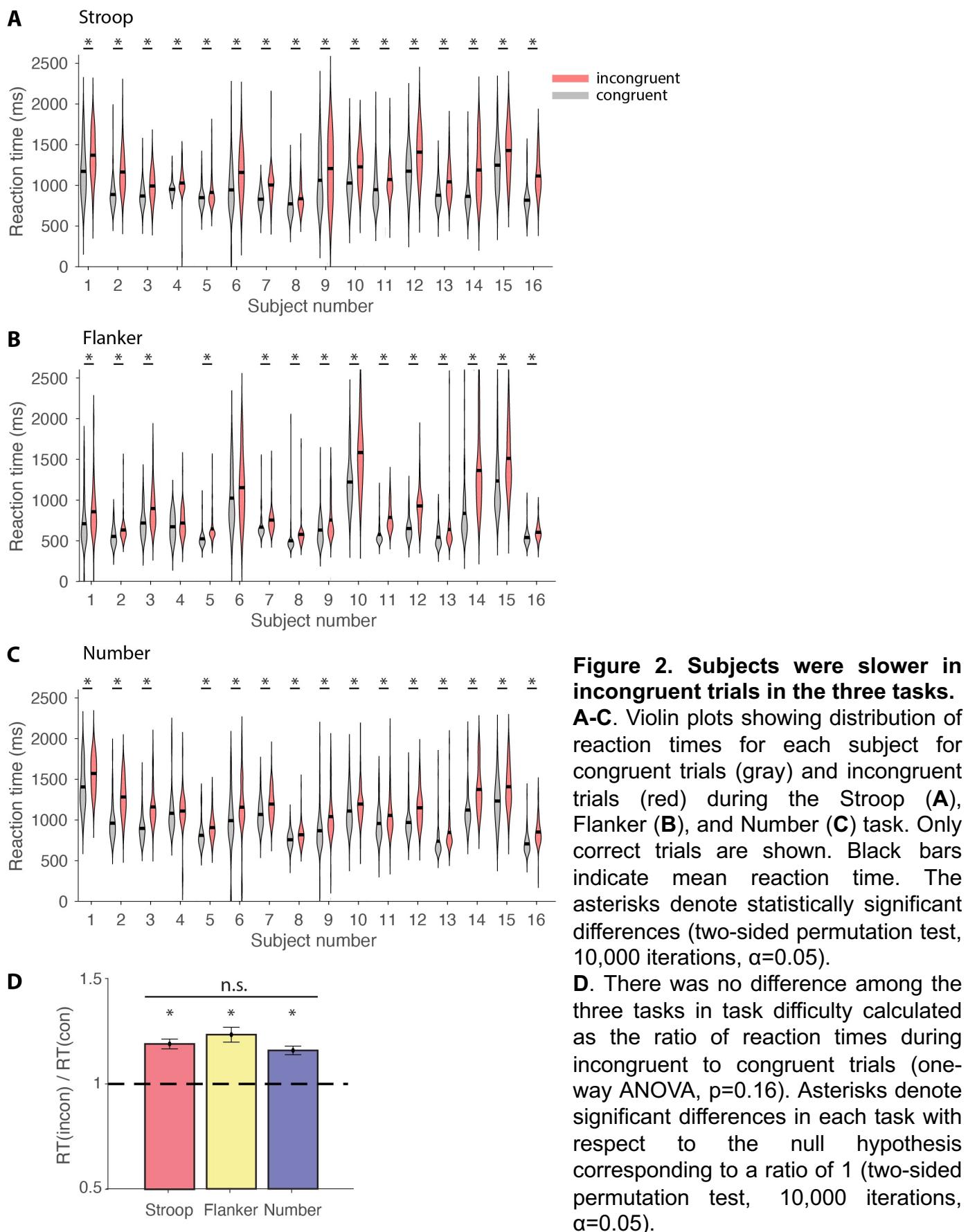


Figure 3

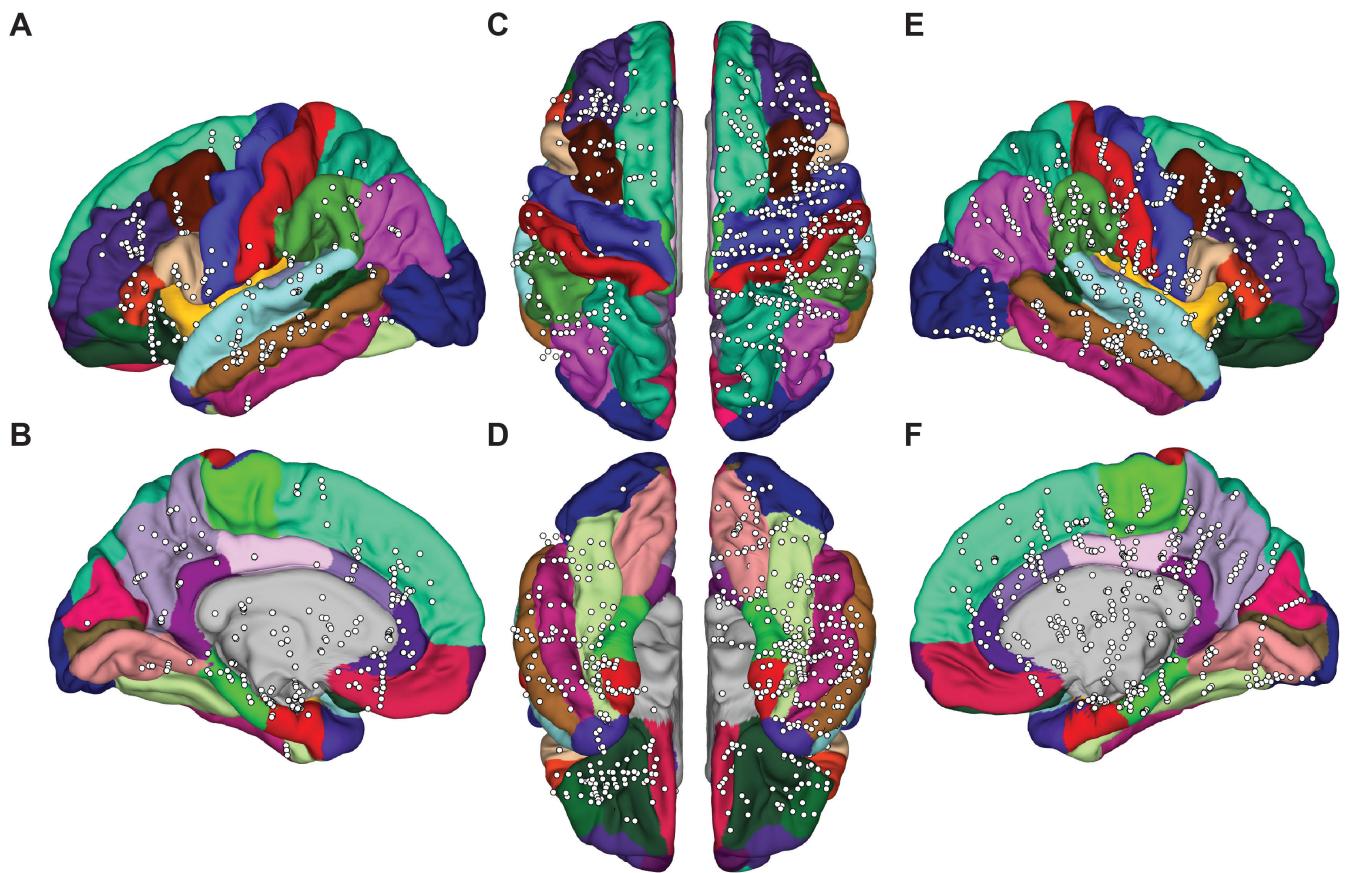


Figure 3. Electrode locations. Location of all n=694 electrodes overlayed on the Desikan-Killiany Atlas shown with different views. **A:** Left lateral; **B:** Left medial; **C:** Superior, whole brain; **D:** Inferior, whole brain; **E:** Right lateral; **F:** Right medial.

Figure 4

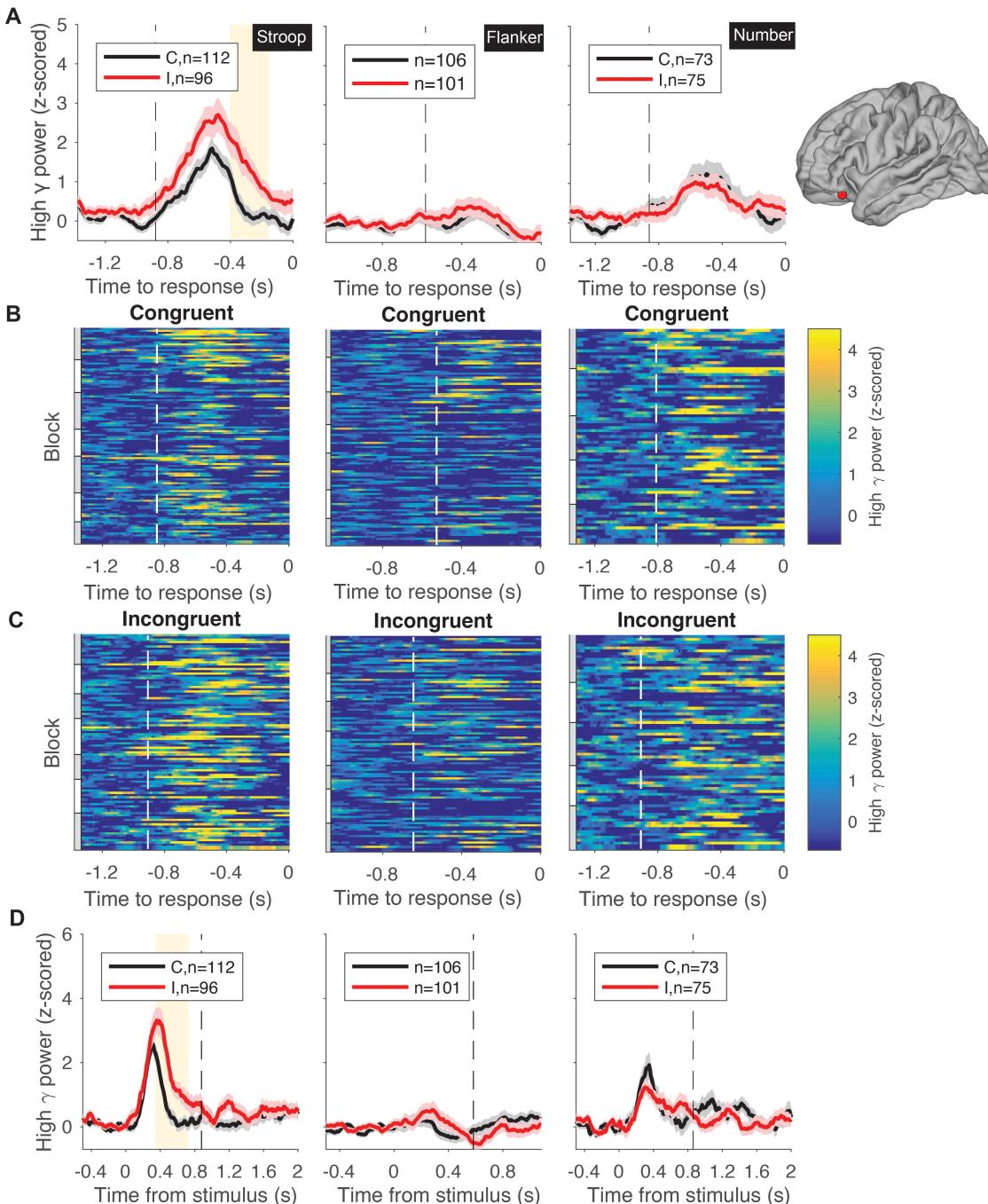


Figure 4. Example electrode in the left orbitofrontal cortex showing conflict modulation in the high-gamma band during the Stroop task. A. The traces show the mean \pm SEM z-scored high-gamma power (70–120 Hz) aligned to behavioral response time for incongruent trials (red) and congruent trials (black) for each of the three tasks (Column 1: Stroop; Column 2: Flanker; Column 3: Number). The vertical dashed lines denote the average stimulus onset. Yellow background indicates statistically significant differences between congruent and incongruent trials (permutation test, 5000 iterations, $\alpha=0.05$, **Methods**). The electrode location is shown on the right. **B-C.** Raster plots showing the neural signals in individual trials (see color scale on the right) for congruent (**B**) and incongruent (**C**) trials. The white dashed lines in the raster plots show the average stimulus onset time. These lines are shifted to the left in **C** compared to **B**, reflecting the longer reaction times during incongruent trials; **Figure 2**. Gray and white bars on the left of the raster plots represent different blocks. **D.** Z-scored high-gamma power (mean \pm SEM) aligned to stimulus onset. Vertical dashed lines denote the average behavioral response time. Yellow background indicates statistically significant difference between incongruent and congruent trials (permutation test, 5000 iterations, alpha=0.05, **Methods**).

Figure 5

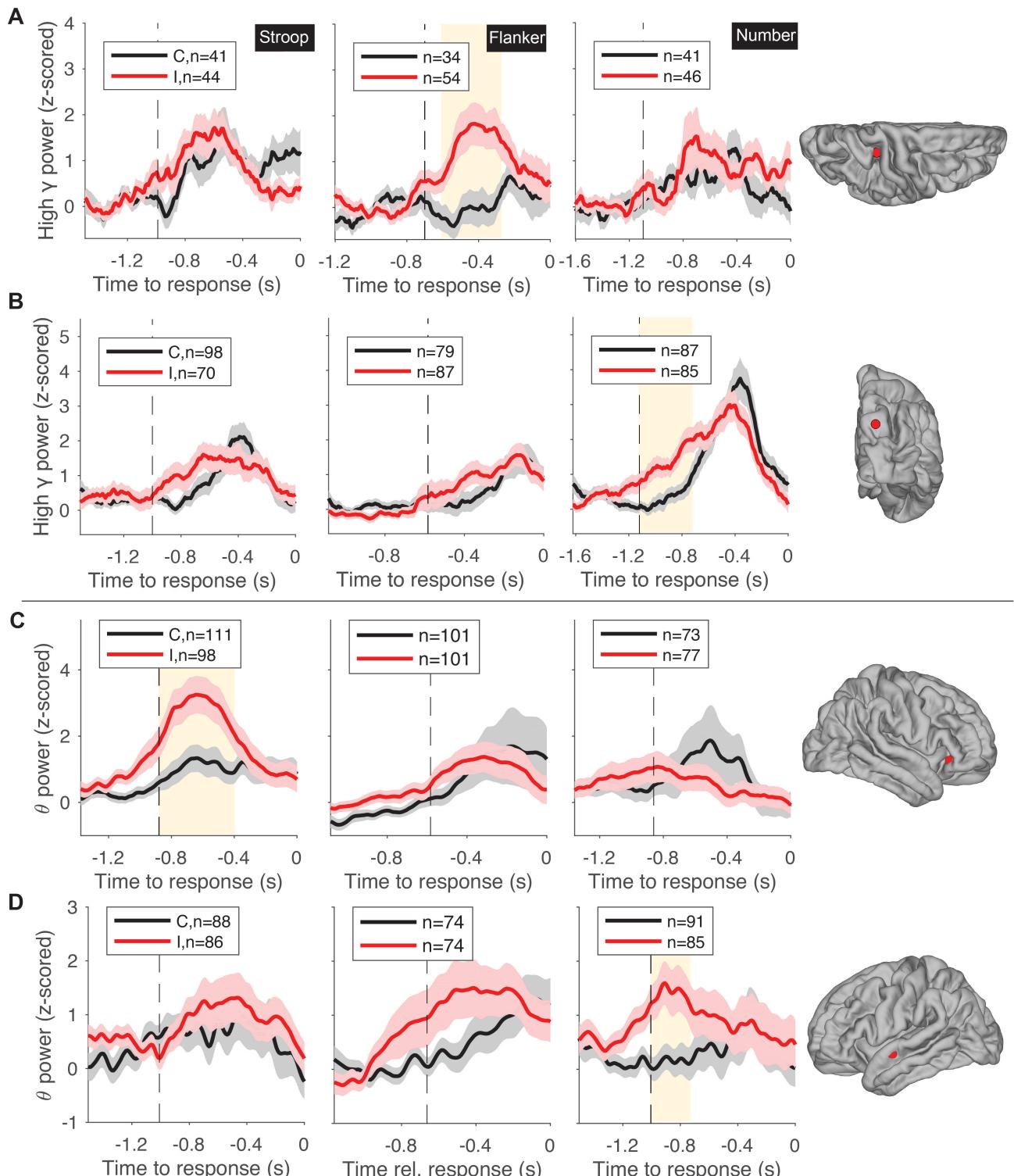


Figure 5. Example electrode showing conflict modulation in high-gamma (A-B) and theta band (C-D) during one task (A: Flanker; B,D: Number; C: Stroop). The traces show mean \pm SEM z-scored high-gamma (A-B) or theta (C-D) power aligned to behavioral response time for incongruent trials (red) and congruent 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 onset. Yellow background indicates statistically significant differences between congruent and incongruent trials (permutation test, 5000 iterations, $\alpha=0.05$, **Methods**). Electrode locations are shown on the right (A: right superior parietal; B: right precuneus; C: right pars triangularis; D: left superior temporal).

Figure 6

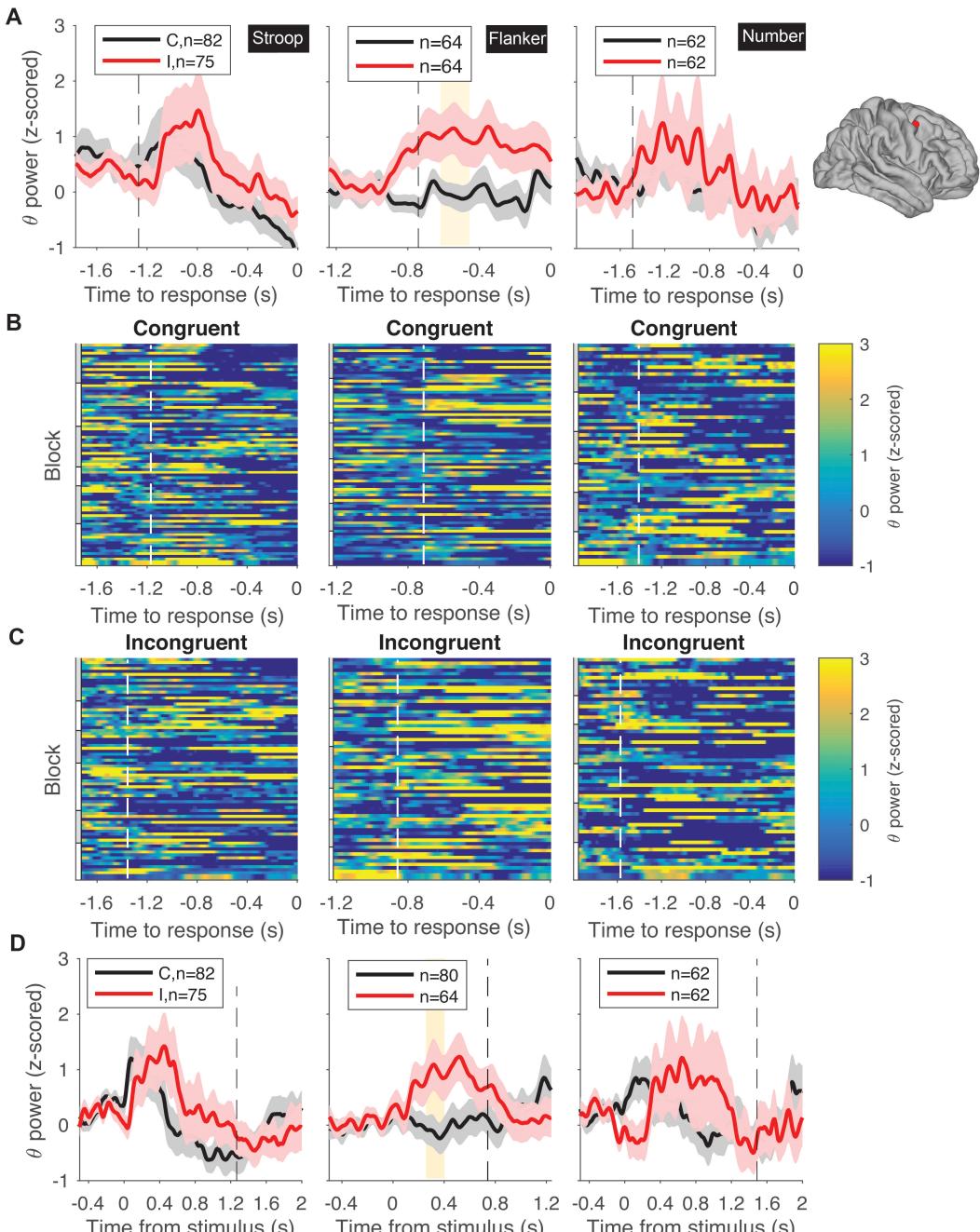


Figure 6. Example electrode in the right precentral cortex showing conflict modulation in the theta band during the Flanker task. **A.** The traces show the mean \pm SEM z-scored theta power (4-8 Hz) aligned to behavioral response time for incongruent trials (red) and congruent trials (black) for each of the three tasks (Column 1: Stroop; Column 2: Flanker; Column 3: Number). The format and conventions follow those in **Figure 4**. The vertical dashed lines denote the average stimulus onset. Yellow background indicates statistically significant differences between congruent and incongruent trials (permutation test, 5000 iterations, $\alpha=0.05$, **Methods**). The electrode location is shown on the right. **B-C.** Raster plots showing the neural signals in individual trials (see color scale on the right) for congruent (**B**) and incongruent (**C**) trials. The white dashed lines in the raster plots show the average stimulus onset time. These lines are shifted to the left in **C** compared to **B**, reflecting the longer reaction times during incongruent trials (**Figure 2**). Gray and white bars on the left of the raster plots represent different blocks. **D.** Z-scored theta power (mean \pm SEM) 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 7

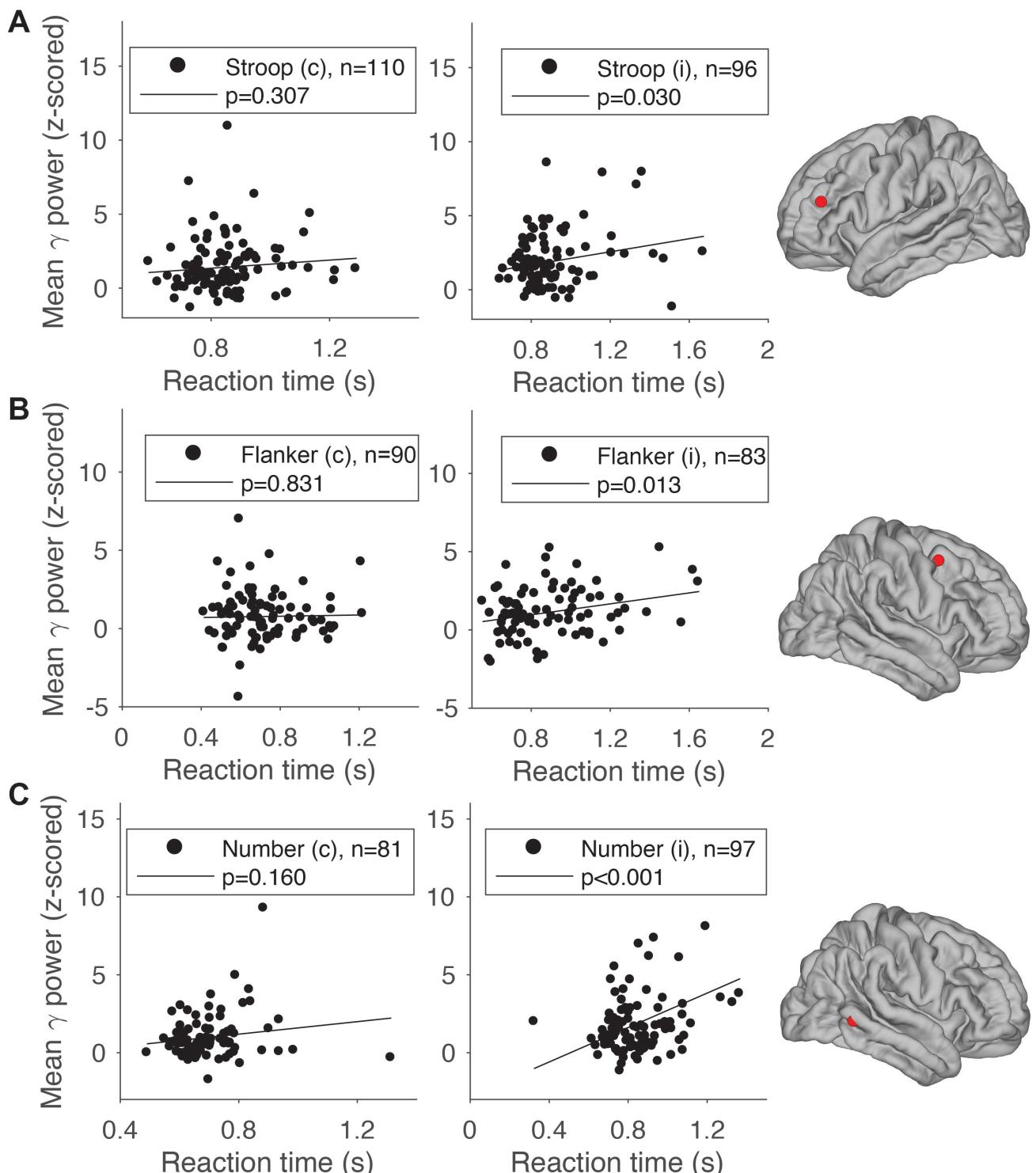
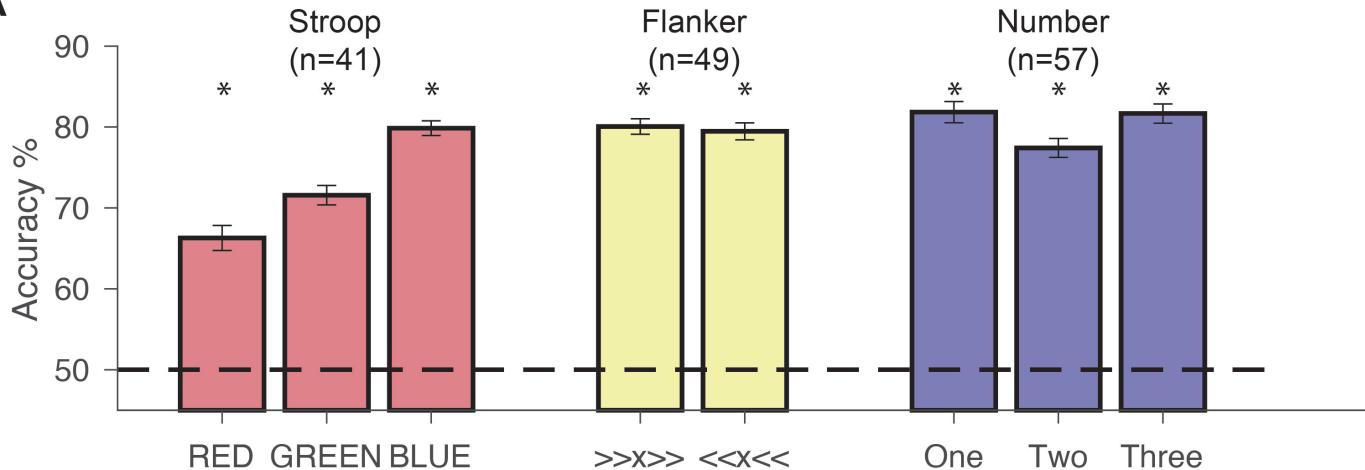


Figure 7. Example conflict modulated responses showing correlation with reaction time. The plots show the mean high-gamma power (z-scored) in each trial as a function of the reaction time for 3 example electrodes during the (A) Stroop (left rostral middle frontal cortex), (B) Flanker (right superior 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 line shows the linear fits. Correlations were statistically significant for incongruent trials (right) but not congruent trials (left) (see p values in legend).

Figure 8

A



B

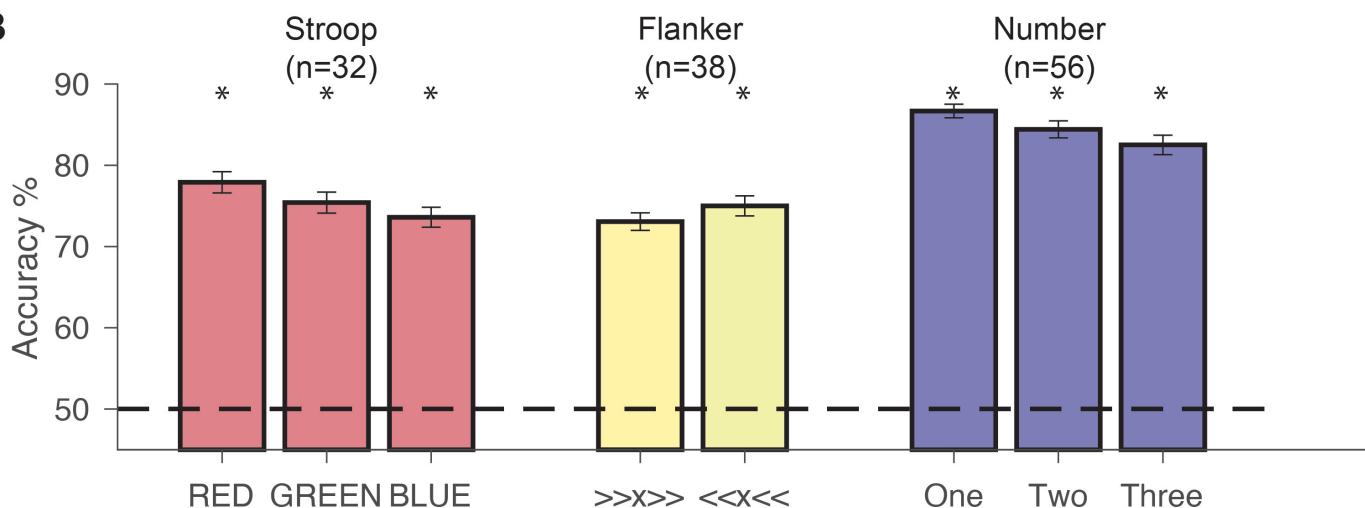


Figure 8. Within-task invariance in population-based decoding of conflict in single trials.

Accuracy of support vector machine (SVM) classifier in discriminating incongruent from congruent trials extrapolating across conditions within each task (within-task invariance) using high-gamma (A) and theta (B) band power.

Stroop task. The first bar labeled “RED” was trained using the “GREEN” trials (as in DEF in **Figure S8**) and “BLUE” trials (as in GHI in **Figure S8**), and tested on “RED” trials (as in ABC in **Figure S8**). A similar procedure was followed for the other combinations: in bar 2, the SVM was trained using “RED” and “BLUE” trials, and tested on “GREEN” trials. In bar 3, the SVM was trained using “RED” and “GREEN” trials, and tested on “BLUE” trials.

Flanker task. In the first bar, the SVM was trained on “>>>>” and “>><>>”, and tested on “<<<<” and “<><<”. In the second bar, training and testing data were reversed.

Number task. In the first bar, the SVM was trained on trials where the correct answers were “two” (as in CD in **Figure S10**) or “three” (as in EF in **Figure S10**), and tested on trials where the correct answers were “one” (as in AB in **Figure S10**). Similarly in bar 2, the SVM was trained on “one” and “three”, and tested on “two”. In bar 3, the SVM was trained on “one” and “two”, and tested on trials whose target answers were “three”.

For each task, the training and testing data for each condition were randomly subsampled to contain an equal number of congruent and incongruent trials. Electrodes that had very few correct trials in any condition were removed from this analysis. Error bars indicate s.e.m. over 50 sessions. The dashed line indicates chance performance (50%). Asterisks denote higher than chance accuracy (permutation test with 10,000 iterations, p<0.001 for all bars).

Figure 9

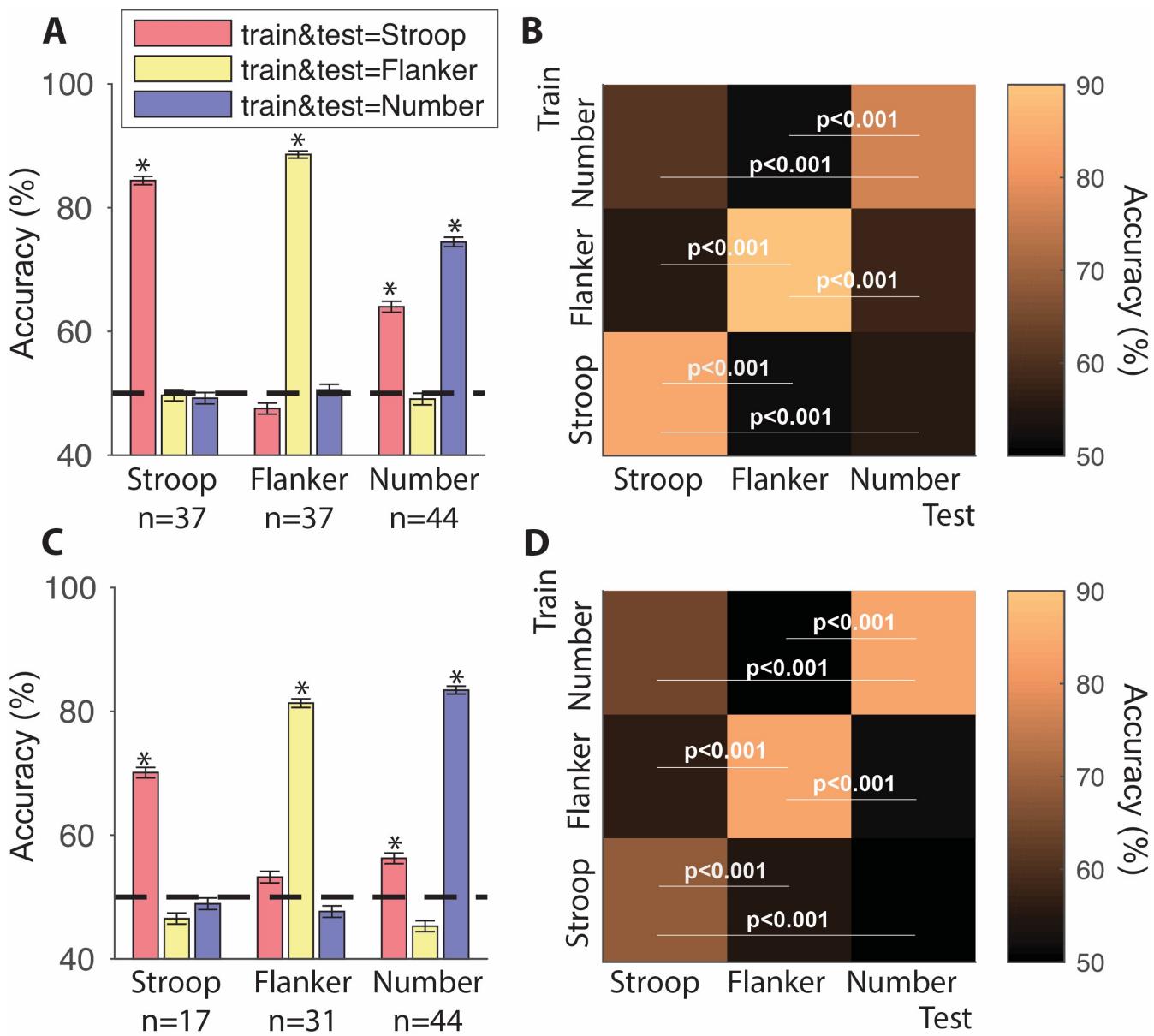


Figure 9. Task-specificity in population-based decoding of conflict in single trials

A, C. Accuracy of SVM classifier in congruent/incongruent discrimination when using a population of Stroop-specific electrodes (first three bars), Flanker-specific electrodes (next three bars), or Number-specific electrodes (last three bars). 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**) and theta (**C**) band power data from the Stroop (red), Flanker (yellow), or Number (blue) tasks. Asterisks indicate that performances are significantly higher than chance (permutation test, 10,000 iterations, one-sided, $p<0.001$). **B, D.** Cross-task training and testing using high-gamma (**B**) and theta (**D**) band power. Here we used the same three populations from part **A** and **C**. 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 S1

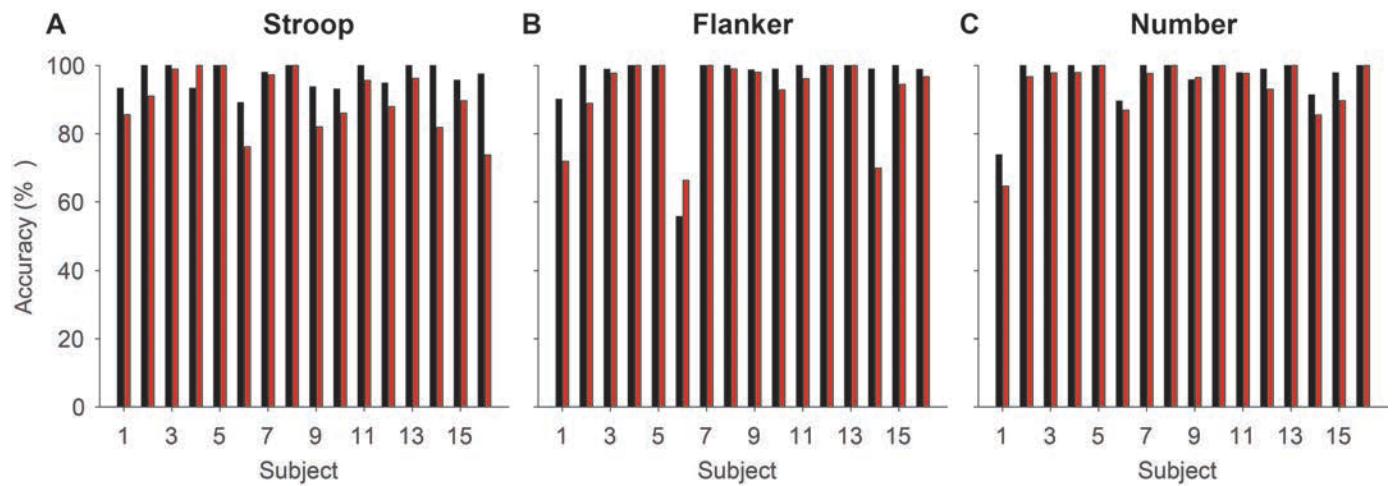


Figure S1. Accuracy of each subject in each task. Black bars indicate congruent trials and red bars incongruent trials.

Figure S2

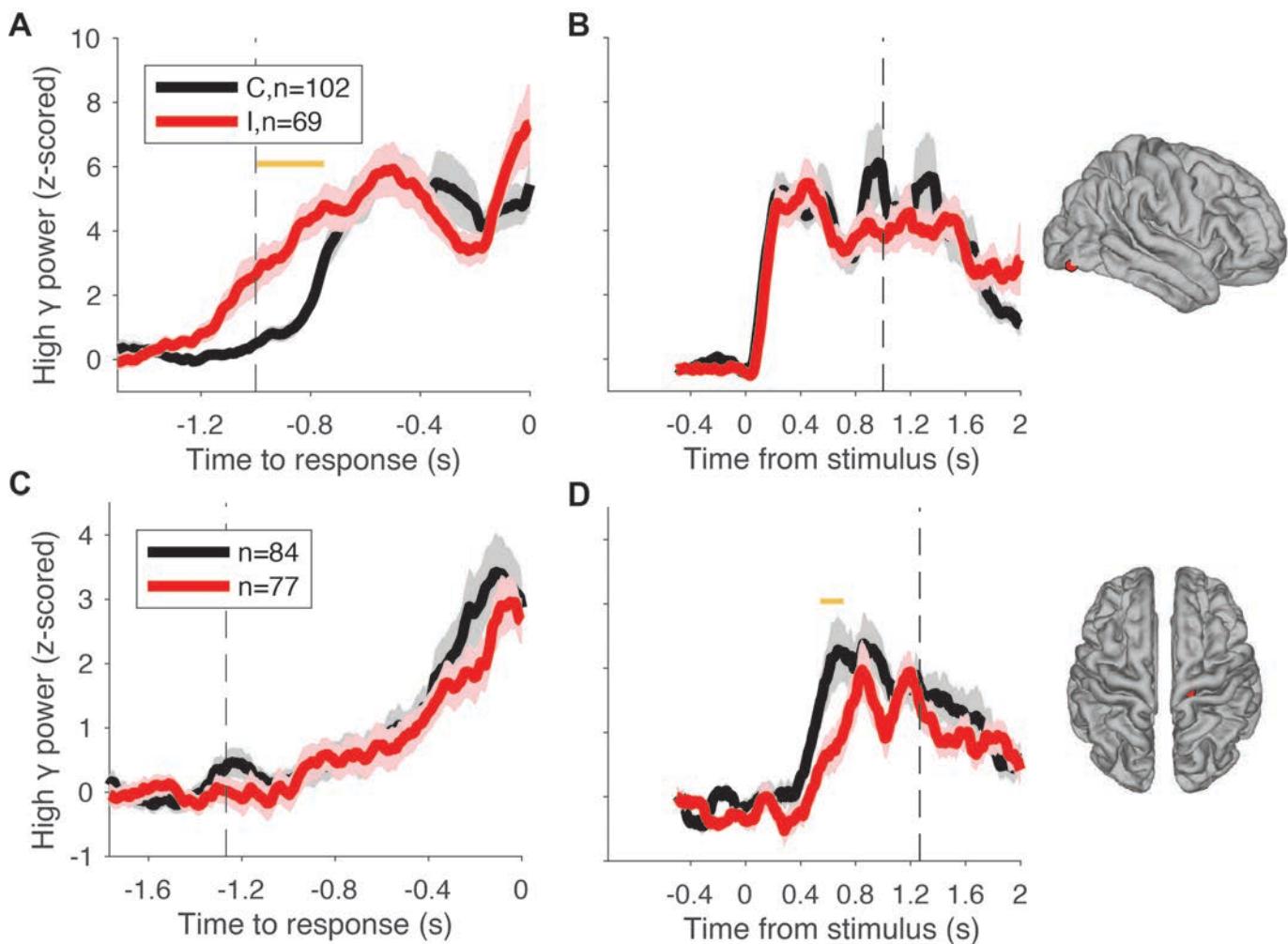


Figure S2. Alignment to stimulus and behavioral responses is critical to interpret conflict modulation signals. An electrode at right lateral occipital cortex showed conflict modulation when the high gamma power (mean \pm SEM, black for congruent and red for incongruent) was aligned to behavioral response (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 \pm 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 thus we do not consider them as conflict-selective.

Figure S3

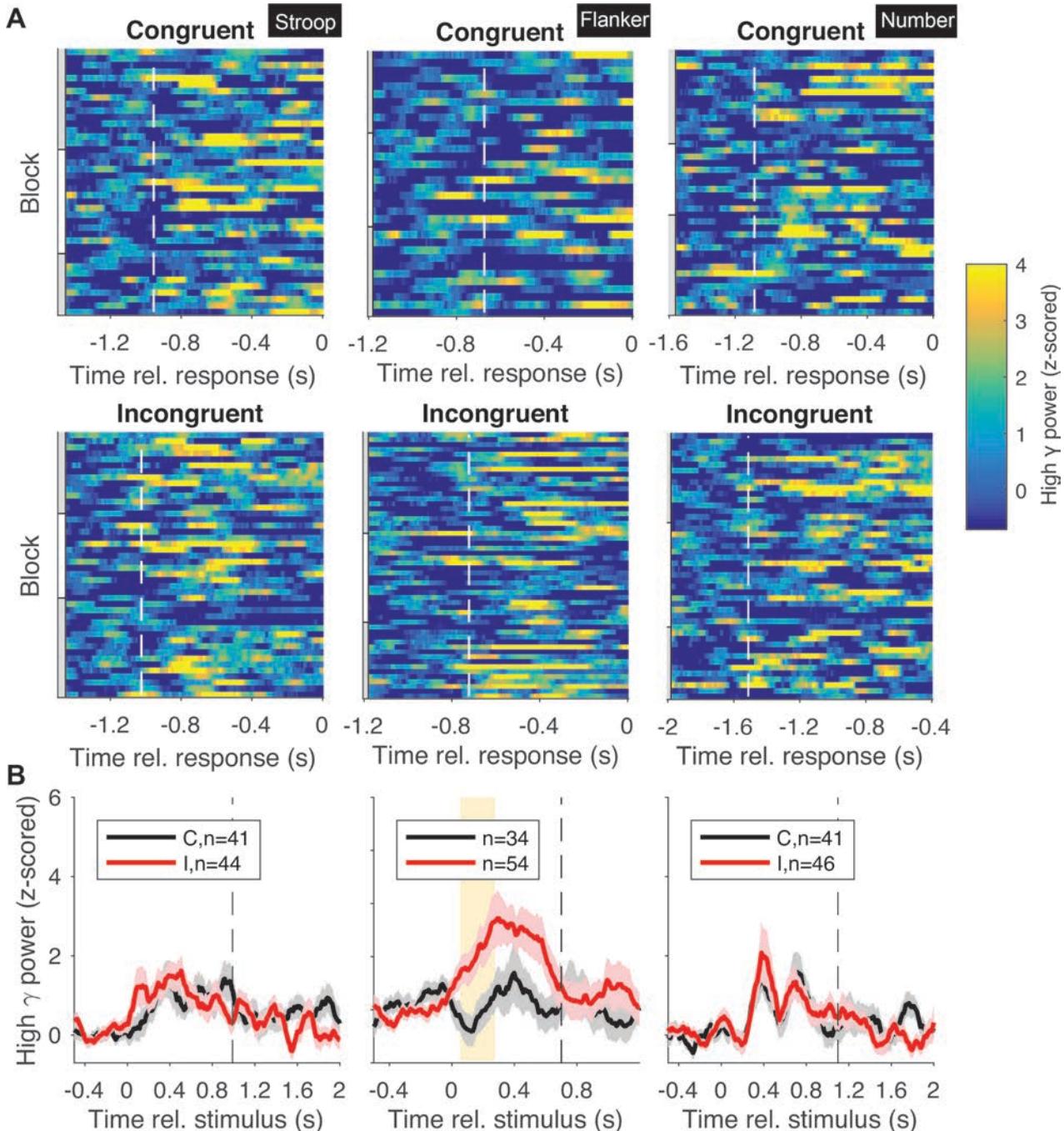


Figure S3. Example Flanker-specific electrode in the high gamma band (same electrode as in **Figure 5A**). An electrode located at the right superior parietal cortex exhibited conflict modulation in the Flanker task only. **A.** Raster plots showing the neural signals in individual trials (see color scale on the right) for congruent (top row) and incongruent (middle row) 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 \pm 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

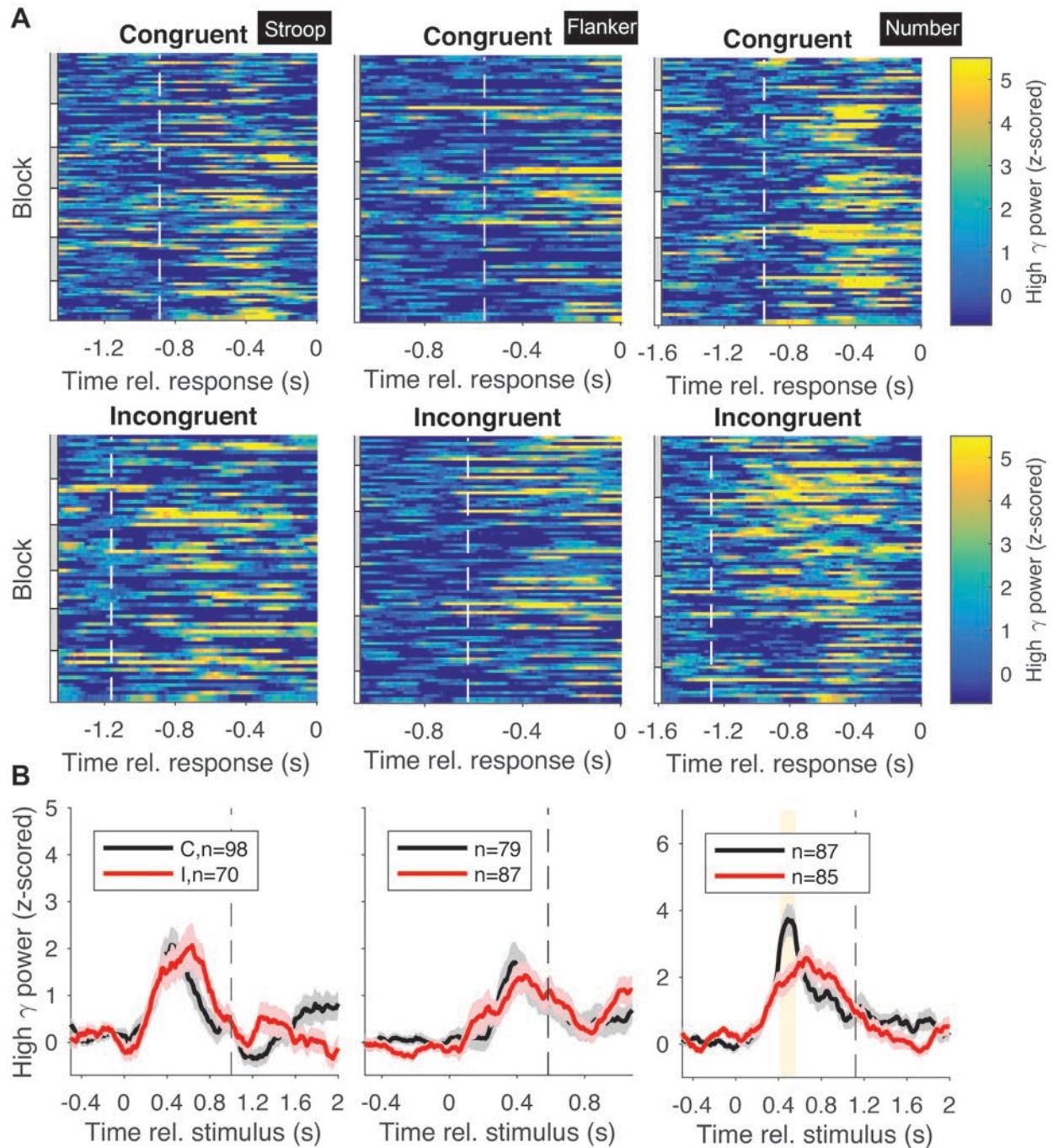


Figure S4. Example Number-specific electrode in the high gamma band (same as in Figure 5B). An electrode located at the right precuneus exhibited conflict modulation in the Number task only. **A.** Raster plots showing the neural signals in individual trials (see color scale on the right) for congruent (top row) and incongruent (middle row) 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 \pm 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

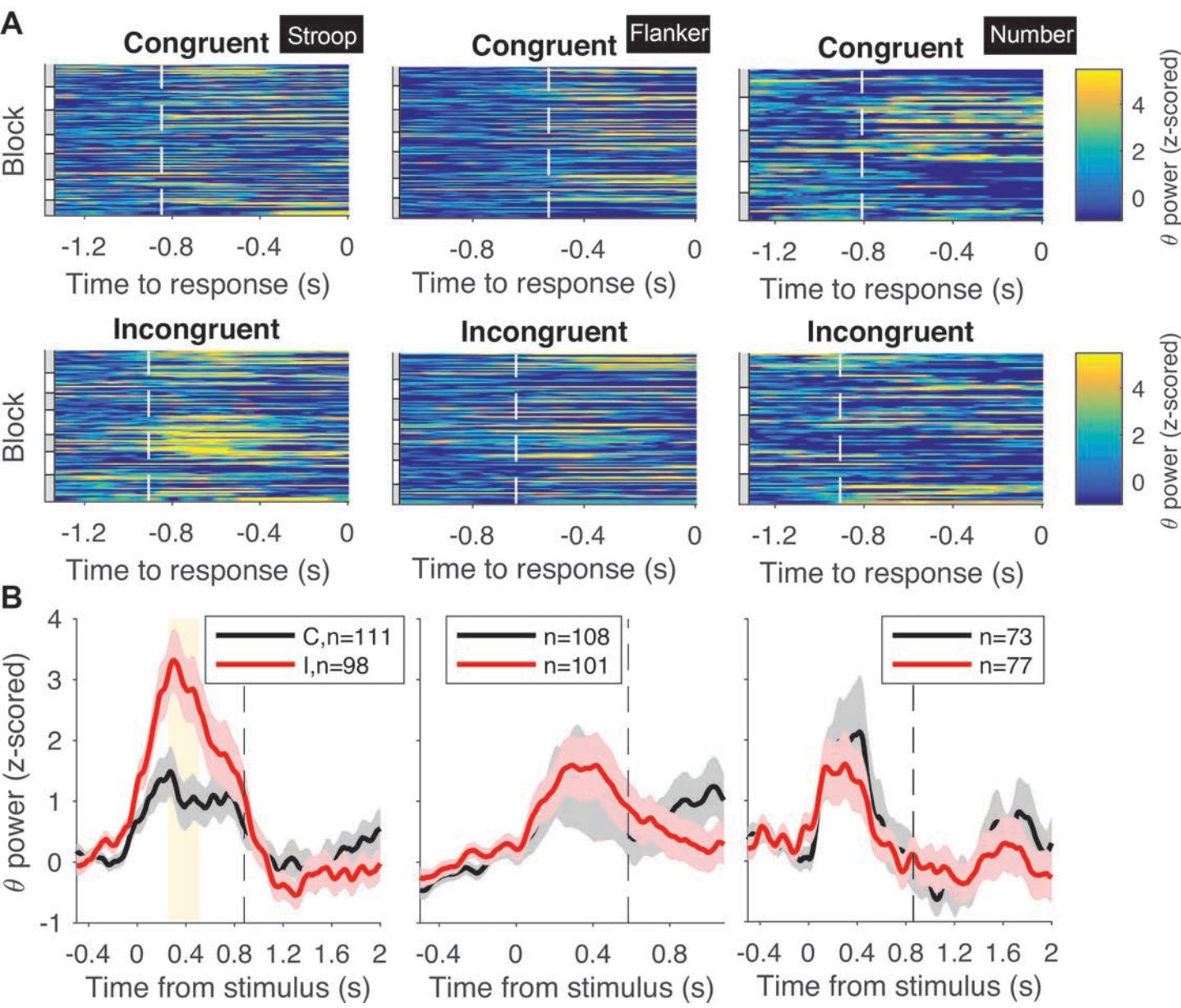


Figure S5. Example Stroop-specific electrode in the theta band (same as in **Figure 6C**). An electrode located at the right pars triangularis exhibited conflict modulation in the Stroop task only. **A.** Raster plots showing the neural signals in individual trials (see color scale on the right) for congruent (top row) and incongruent (middle row) 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 theta power (mean \pm 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 S6

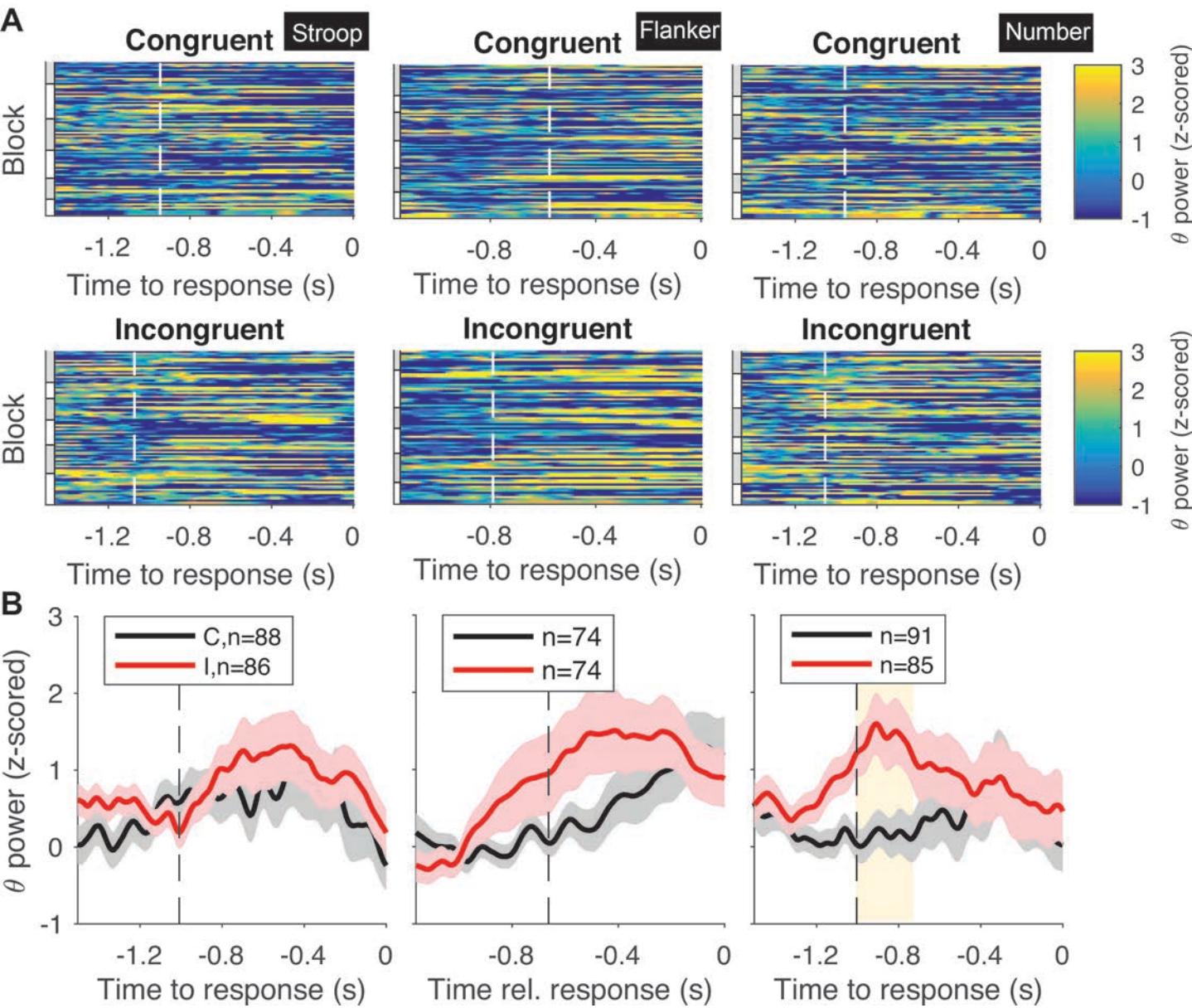
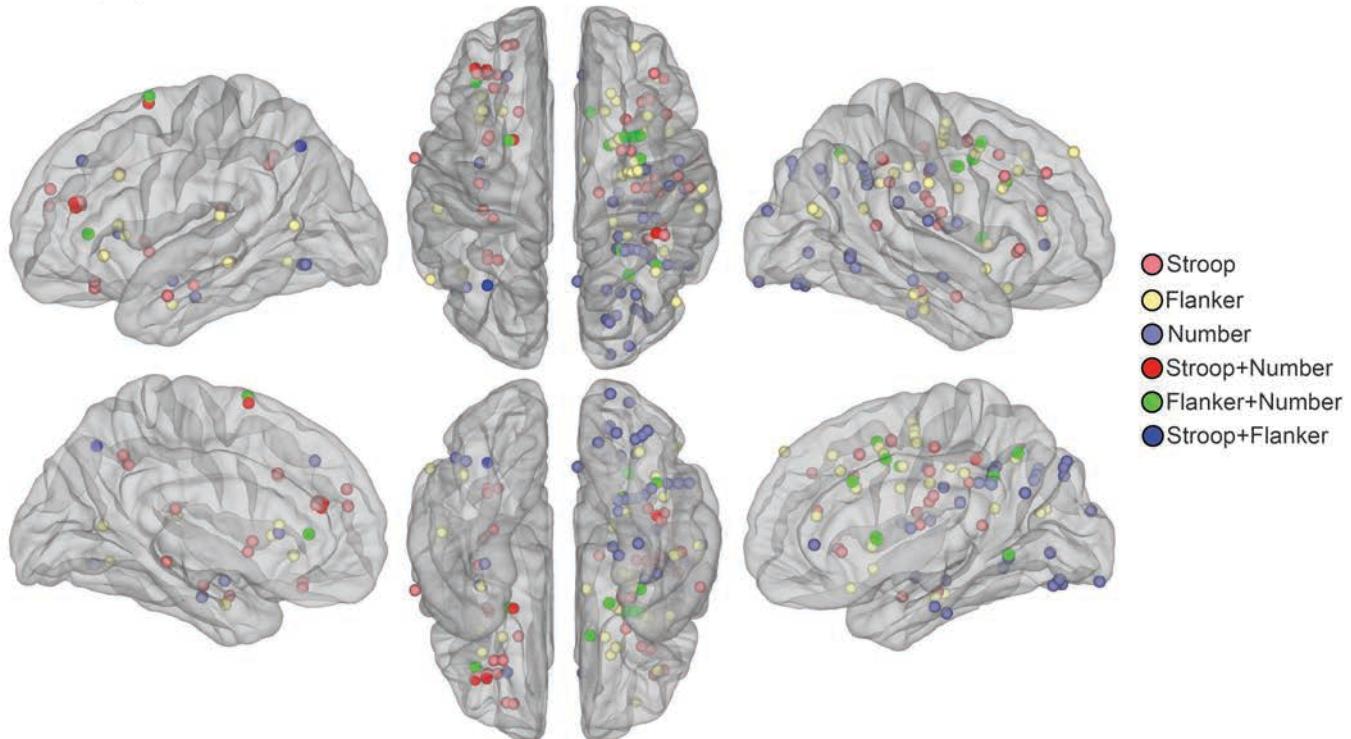


Figure S6. Example Number-specific electrode in the theta band (same as in **Figure 6D**). An electrode located at the left superior temporal cortex exhibited conflict modulation in the Number task only. **A.** Raster plots showing the neural signals in individual trials (see color scale on the right) for congruent (top row) and incongruent (middle row) 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 theta power (mean \pm 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 S7

A High gamma band



B Theta band

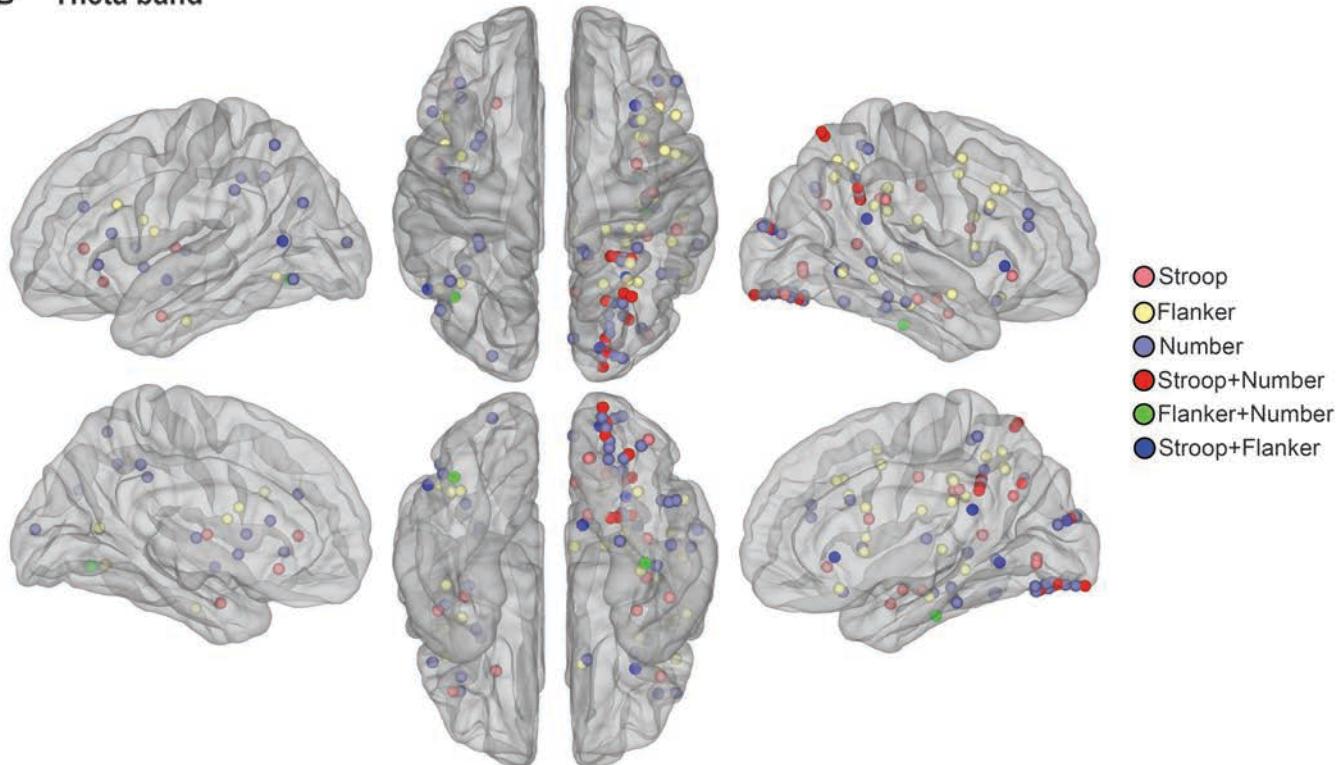


Figure S7. Electrodes exhibiting conflict modulation in high gamma (A) and theta (B) band. Specific locations of these electrodes can be found in Table S3 and S4. We didn't find any electrode that was conflict-selective for all the three tasks in all the frequency bands we analyzed.

Figure S8

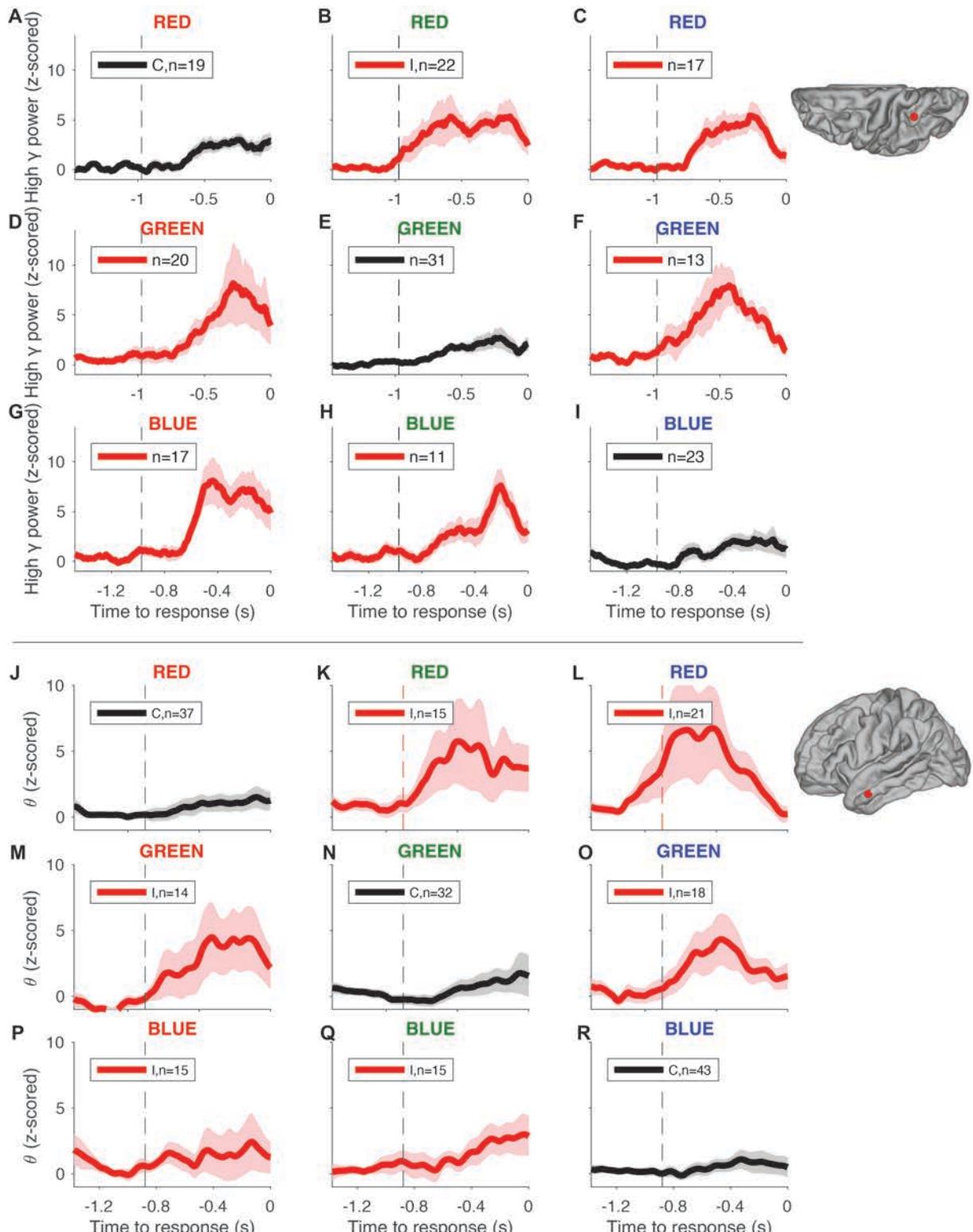


Figure S8. Example Stroop-specific electrodes show within-task invariance (A-I: high gamma band, left inferior parietal; J-R: theta band, left superior temporal).

Z-scored high-gamma or theta power ($\text{mean} \pm \text{SEM}$) aligned to behavioral response time (black for congruent and red for incongruent). Vertical dashed lines denote the average stimulus onset. Subplot titles indicate specific stimulus types. Conflict modulation occurs in all incongruent color/word combinations.

Figure S9

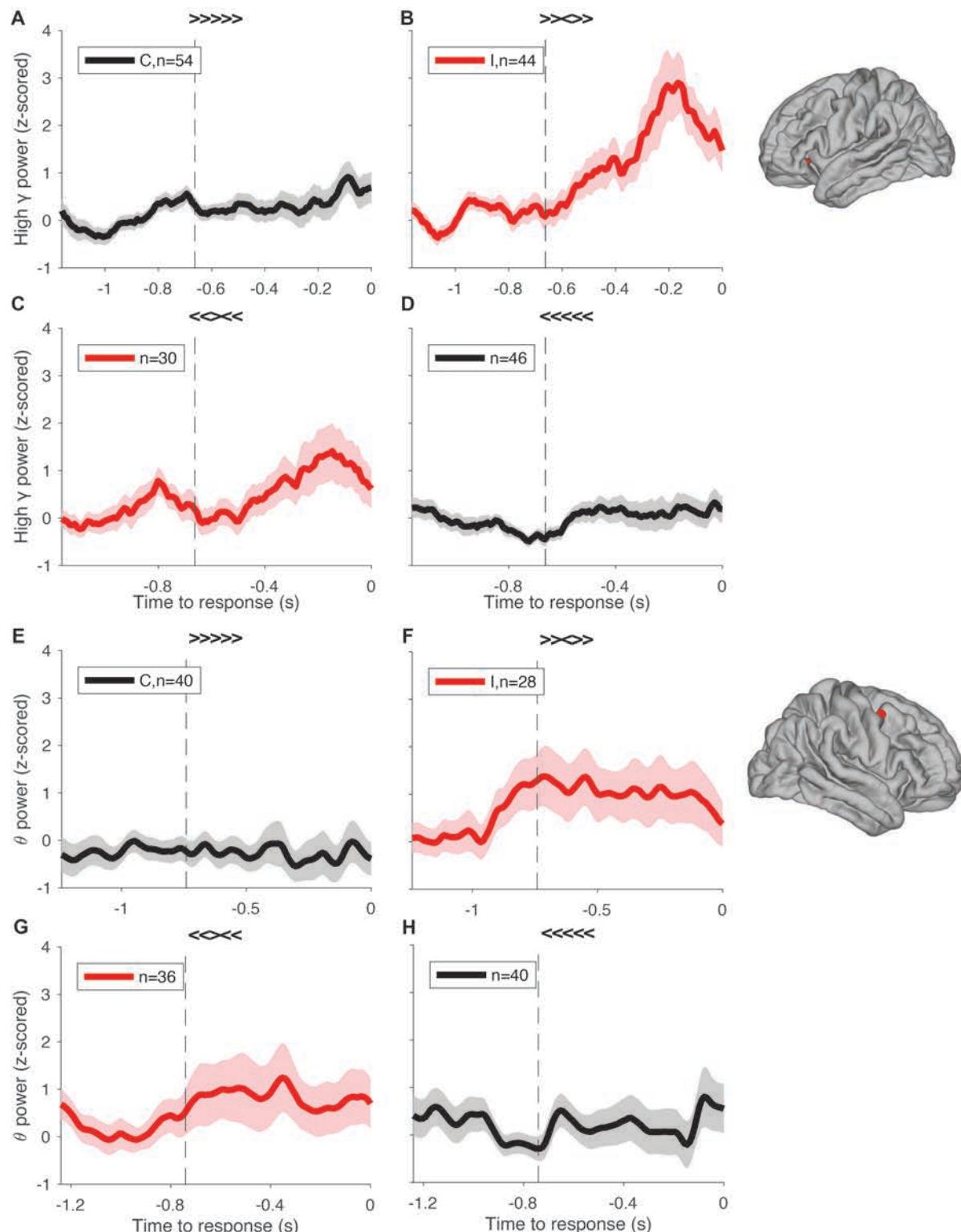


Figure S10. Example Flanker-specific electrodes show within-task invariance (A-D, high gamma, left orbitofrontal; E-H, theta, right precentral). Z-scored high-gamma or theta power (mean \pm SEM) aligned to behavioral response time (black for congruent and red for incongruent). Vertical dashed lines denote the average stimulus onset. Subplot titles indicate specific stimulus types. Conflict modulation occurs in all incongruent target/flanker combinations.

Figure S10

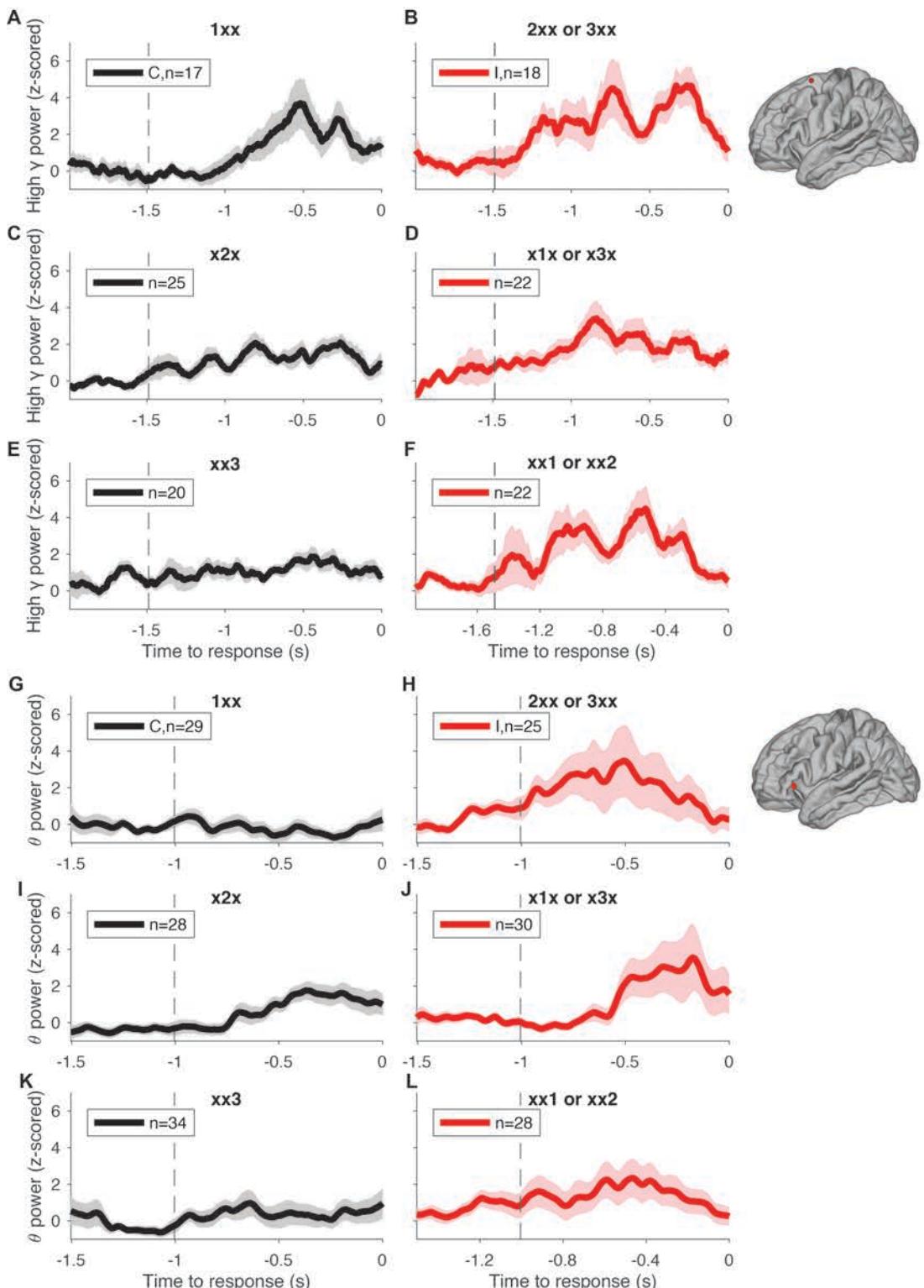


Figure S10. Example Number-specific electrodes show within-task invariance (A-F, high gamma, left superior frontal; G-L, theta, left pars triangularis). Z-scored high-gamma or theta power (mean \pm SEM) aligned to behavioral response time (black for congruent and red for incongruent). Vertical dashed lines denote the average stimulus onset. Subplot titles indicate specific stimulus types. Conflict modulation occurs in all incongruent target/distractor combinations.

Figure S11

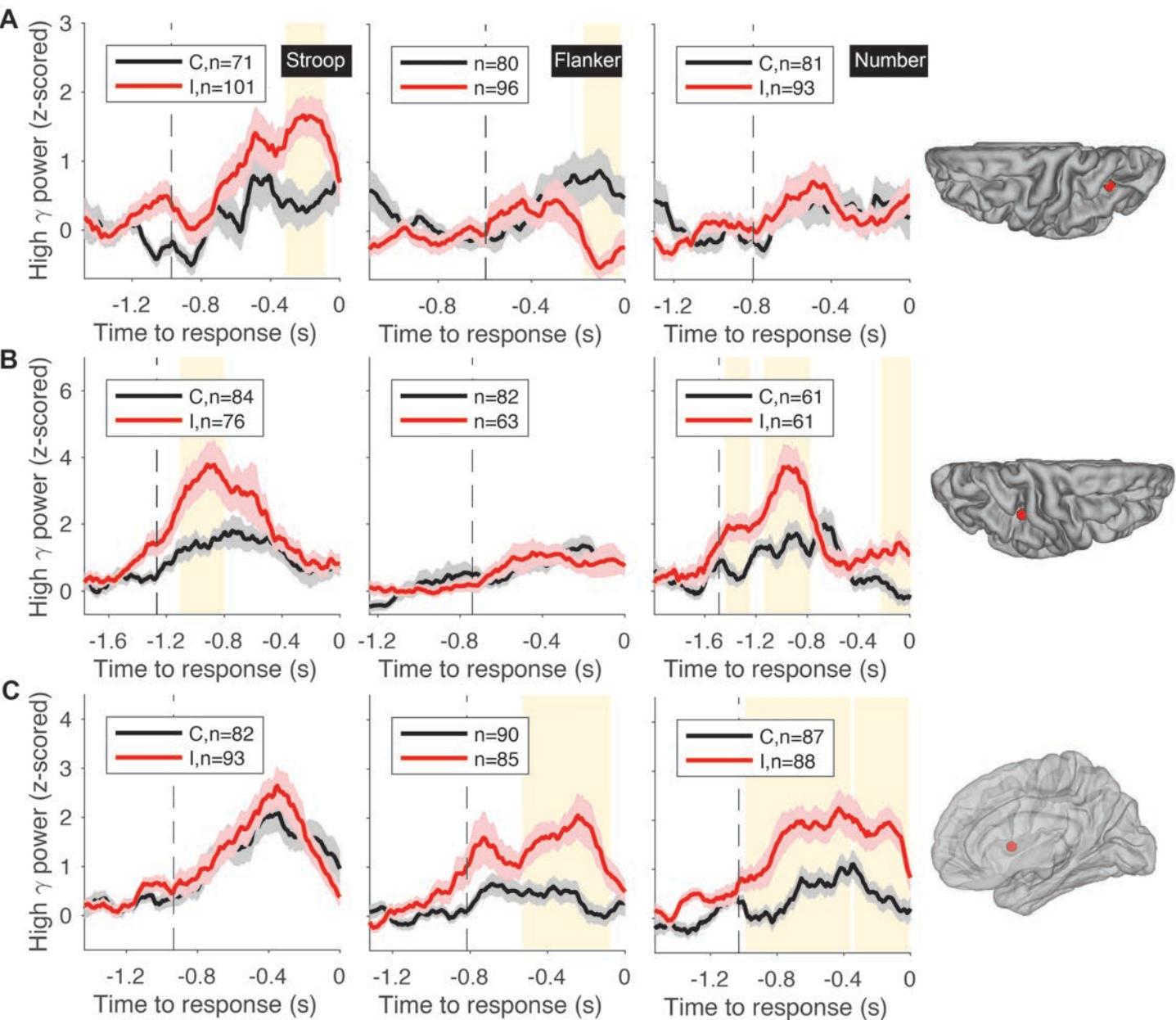


Figure 11. Example electrodes showing conflict modulation in two tasks

A. An electrode located in the left inferior parietal (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 \pm SEM, black for congruent and red for incongruent) aligned to behavioral response time. Vertical dashed lines denote the average stimulus onset time. Yellow background indicates statistically significant differences between congruent and incongruent trials (permutation test, 5000 iterations, alpha=0.05, **Methods**). **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 insula exhibited conflict modulation in the Flanker and Number tasks but not in the Stroop task. Brain was rendered transparent for better visualization of electrodes in deep structures.

Figure S12

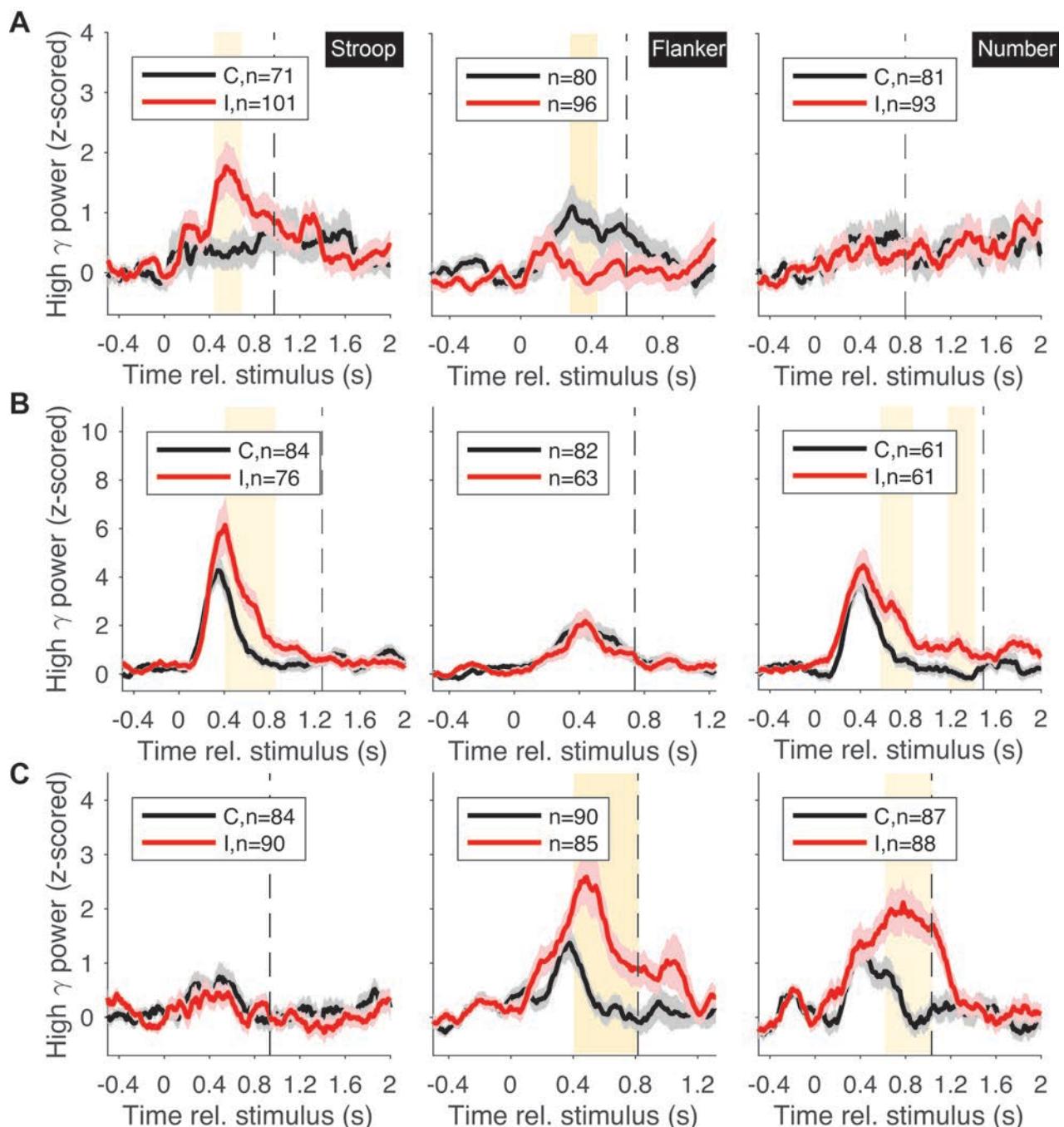


Figure S12. Example dual-task electrodes. Stimulus aligned responses for the electrodes in **Figure S11**.

Figure S13

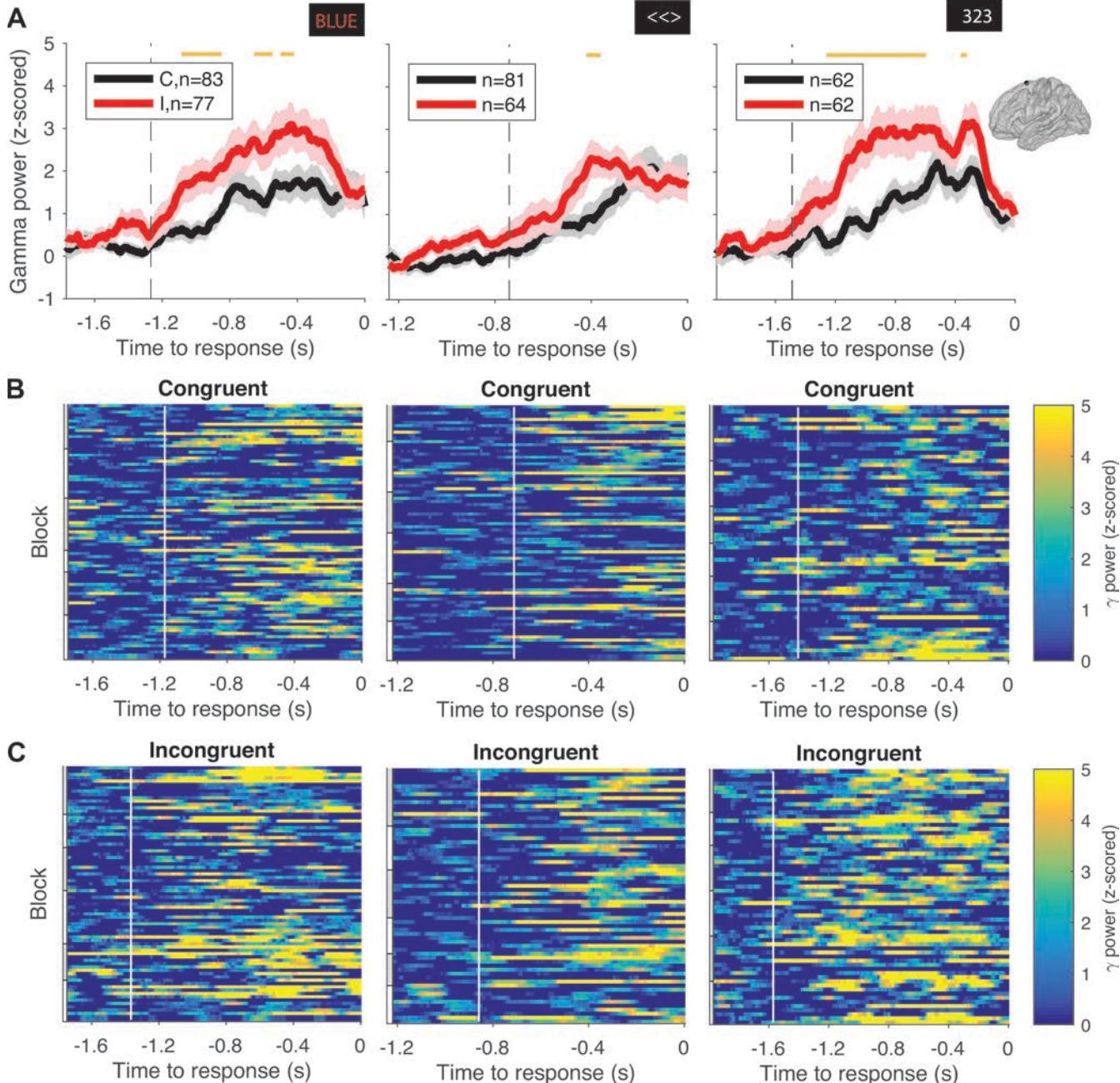


Figure S13. One of two task invariant electrodes. Using global referencing instead of bipolar referencing, a shorter duration threshold, and less stringent test (t-test) to distinguish incongruent and congruent trials (50 ms instead of 150 ms), we found two electrodes out of 748 electrodes (0.3%) that showed task invariance, one of them is shown here. Yellow bars indicate significant windows. This electrode was located in the left superior frontal region.

Table S1: Subject information. Information about each participant and number of blocks completed. Bolded entries indicate subjects that performed fewer or more than the default target number of blocks (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 the right and left hemisphere for each location.

| 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 S3: 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. Sum refers to the total number of conflict-modulated electrodes in each row and ‘total in location’ shows the total number of electrodes analyzed in that regions. 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 S4: 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. Sum refers to the total number of conflict-modulated electrodes in each row and ‘total in location’ shows the total number of electrodes analyzed in that regions. S=Stroop, F=Flanker, N=Number.

| Location | One task only | | | Two tasks | | | All | Sum |
|--------------------------|---------------|-----------|-----------|-----------|-----------|----------|----------|------------|
| | Stroop | Flanker | Number | S+F | S+N | 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 |

Table S5: Location of visual-selective electrodes. For each location, the table reports the number of electrodes that show visual selectivity during Stroop, Flanker, and Number task respectively. Sum refers to the total number of response electrodes in each row and ‘total in location’ shows the total number of electrodes analyzed in that region.

| 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 S6: Location of motor-selective electrodes. For each location, the table reports the number of electrodes that show motor selectivity for verbal and keypress. Sum refers to the total number of response electrodes in each row and ‘total in location’ shows the total number of electrodes analyzed in that region.

| 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 |

Table S7: Number of conflict-modulated electrodes considering other frequency bands

| Frequency Band | Time-bandwidth product, taper, moving window | One task only | | | Two tasks | | | All | Sum |
|------------------------|--|---------------|---------|--------|-----------|-----|-----|-----|-----|
| | | Stroop | Flanker | Number | S+F | S+N | 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 |