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Neural mechanisms of cognitive dissonance (revised): An EEG study

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Commercial Interest:

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3 Abbreviated title: **Neural Mechanisms of Cognitive Dissonance**

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37 **Abstract**

38 Cognitive dissonance theory suggests that our preferences are modulated by the mere act of  
39 choosing. A choice between two similarly valued alternatives creates psychological tension  
40 (cognitive dissonance) that is reduced by a post-decisional reevaluation of the alternatives.  
41 Our study demonstrates that choices associated with stronger cognitive dissonance trigger a  
42 larger negative fronto-central evoked response similar to *error-related negativity* (ERN),  
43 which has in turn been implicated in general performance monitoring. Furthermore, the  
44 amplitude of the evoked response is correlated with the reevaluation of the alternatives. We  
45 also found a link between individual neural dynamics (long-range temporal correlations—  
46 LRTC) of the fronto-central cortices during rest and follow-up neural and behavioral effects  
47 of cognitive dissonance. Individuals with stronger resting-state LRTC demonstrated a greater  
48 post-decisional reevaluation of the alternatives and larger evoked brain responses associated  
49 with stronger cognitive dissonance. Thus, our results suggest that cognitive dissonance is  
50 reflected in both resting-state and choice-related activity of the prefrontal cortex as part of the  
51 general performance-monitoring circuitry.

52 **Significance Statement**

53 Contrary to traditional decision theory, behavioral studies repeatedly demonstrate that our  
54 preferences are modulated by the mere act of choosing. Difficult choices generate  
55 psychological (cognitive) dissonance, which is reduced by the post-decisional devaluation of  
56 unchosen options. We found that decisions associated with a higher level of cognitive  
57 dissonance elicited a stronger negative fronto-central deflection that peaked ~60 ms after the  
58 response. This activity shares similar spatial and temporal features as error-related negativity  
59 (ERN)—the electrophysiological correlate of performance monitoring. Furthermore, the

60 fronto-central resting-state activity predicted the individual magnitude of preference change  
61 and the strength of cognitive dissonance-related neural activity.

62

63 **Introduction**

64

65 Normative decision theory suggests that our actions reflect our preferences, whereas the  
66 influential theory of “cognitive dissonance” (Festinger, 1957) postulates that our actions  
67 shape our preferences. Numerous studies have shown that when a person must select between  
68 two equally attractive items, the act of choosing one item will induce a preference change  
69 (Izuma et al., 2010, for a review). The theory of cognitive dissonance suggests that such  
70 difficult choices could cause psychological discomfort (cognitive dissonance), which forces  
71 people to engage mechanisms of conflict reduction and preference change (see Harmon-Jones  
72 & Harmon-Jones, 2008, for a review). According to the *action-based model* of cognitive-  
73 Dissonance, activity in the posterior medial frontal cortex (pmMFC) underlies detection of  
74 cognitive conflicts and the reduction of cognitive dissonance (Amodio et al., 2004; Carter,  
75 1998; Izuma et al., 2010). Nevertheless, the neurocomputational foundation of cognitive  
76 dissonance remains unclear. Here, we further studied the role of the pmMFC in cognitive  
77 dissonance and preference change.

78 Interestingly, the pmMFC has also been implicated in the generation of a “reward prediction  
79 error” signal when the outcome of an action differs from the expected one (Cohen &  
80 Ranganath, 2007; Holroyd & Coles, 2002; Nieuwenhuis et al., 2004; Rushworth et al., 2007;  
81 see also Botvinick, 2007). This signal presumably guides future action selection by updating  
82 predictions of action values (Niv, 2009). Involvement of the pmMFC in cognitive dissonance  
83 and general performance monitoring may suggest that cognitive dissonance, general action  
84 monitoring, and reinforcement learning may share neural mechanisms. Thus, we explored  
85 whether *difficult choice*-induced preference changes can be driven by a neural mechanism  
86 similar to the general mechanism of performance monitoring and behavioral adjustment.

87 We further hypothesized that choice-induced preference changes depend on resting-state  
88 pmMFC neuronal dynamics. Recent neuroimaging studies have shown that performance in the  
89 motor task (Smit, Linkenkaer-Hansen, & Geus, 2013) and perceptual tasks (Palva et al.,  
90 2013) may be related to the long-range temporal correlations (LRTC) of neuronal oscillations  
91 recorded at rest conditions. Importantly, LRTC indicate the presence of a scale-free structure  
92 of neuronal activation on multiple time scales that is vital for optimal neuronal processing in  
93 the human brain (Hardstone et al., 2012; Linkenkaer-Hansen et al., 2001; Palva et al., 2013).  
94 Here we suggest that the magnitude of cognitive dissonance can be predicted by the resting-  
95 state neuronal dynamics recorded with an EEG before a cognitive dissonance-inducing task.

96 Specifically, we hypothesized that LRTC and the amplitude of frontal alpha oscillations  
97 would correlate with the behavioral and electrophysiological indices of dissonance-induced  
98 preference change.

99 In order to clarify the mechanism of cognitive dissonance, we used an electrophysiological  
100 signature of behavioral error monitoring—the error-related negativity (ERN) component, a  
101 negative fronto-central deflection in the event-related potential (ERP). ERN is generated in  
102 the pMFC (Debener, 2005; Holroyd et al., 2004; Holroyd & Coles, 2002; Ridderinkhof et al.,  
103 2004) and has been associated with processing errors (Holroyd, Nieuwenhuis, Yeung, &  
104 Cohen, 2003), monitoring of action outcomes (Luu, Tucker, & Makeig, 2004), and behavioral  
105 adjustments (Gehring et al., 2011).

106 The decrease in ratings for rejected items—also known as *Spread of Alternatives* (SoA)—has  
107 been repeatedly demonstrated under the “free-choice paradigm” (Brehm, 1956; Coppin et al.,  
108 2010; Gerard & White, 1983; Shultz, Leveille & Lepper, 1999; Lieberman et al., 2001). Here,  
109 we tested the hypothesis that choice-induced preference changes are associated with a  
110 response-locked negative ERP similar to ERN: We expected that a larger ERN-like activity  
111 would be generated during difficult decisions than easy decisions. We recorded ERPs during  
112 both the free-choice paradigm and the Eriksen flanker task (Eriksen & Eriksen, 1974), the  
113 latter of which can be used as an ERN “functional localizer” task. Overall, our approach  
114 allowed us to investigate similarity between neural mechanisms involved in choice-induced  
115 preference changes and more general reinforcement-learning mechanisms.

116

## 117 **Materials & Methods**

### 118 *Participants*

119 Forty-five right-handed, healthy participants (20 males, mean age  $22.17 \pm 2.68$ ) were  
120 recruited and provided a small amount of compensation (equivalent to \$12–15 US dollars).  
121 Participants were instructed to fast for at least 3 hours before the study.

122 All 45 participants underwent a version of the free-choice paradigm (Izuma et al., 2010). For  
123 24 participants (11 of whom were males), we also recorded classical ERN during the Eriksen  
124 flanker task (see below for details). Three participants were excluded from the analysis of the  
125 free-choice paradigm due to clear instructional misunderstanding. Thus, 42 and 24 subjects  
126 participated in the analysis of the free-choice paradigm and Eriksen flanker task, respectively.

127 All participants had normal or corrected-to-normal vision and received no regular  
128 medications. None of the subjects had a history of neurological or psychiatric illness. The  
129 study protocol was approved by the local ethics committee.

130

131

## 132 ***Experimental Tasks***

### 133 *Free-choice paradigm*

134 *Stimuli:* A set of 446 digital color photos of *snack foods* on a white background (chocolate,  
135 chips, small fruits or vegetables, cheese) were used as stimuli. The items were selected from a  
136 larger dataset during a pre-study in order to incorporate the most familiar food items available  
137 in the local market. The price of each item was below \$8 US dollars (500 rubles). The photos  
138 were projected onto a screen, with a visual angle of 4.772° vertically and 7.62° horizontally.

139 *Procedure:* The basic free-choice paradigm consisted of three main parts: I. Preference task I,  
140 II. Choice task, and III. Preference task II.

141 During *Preference task I*, participants rated a set of 446 food items using an 8-point Likert  
142 scale (1 = “I don’t like it at all” to 8 = “I like it a lot”). Each item appeared at the center of the  
143 screen for 3 seconds. During the *Choice task*, two foods were presented on the screen at the  
144 same time (up to 210 pairs altogether). In *Self-trials*, participants were instructed to choose  
145 one food item that they preferred. In order to increase their motivation, participants were  
146 informed that they would receive one of the selected foods along with monetary  
147 compensation. Unknown to participants, the pairs were created using a computational  
148 algorithm based of participants’ ratings during *Preference task I*: one-half of the pairs  
149 included two highly preferred foods (rated between 6 and 8—these trials were defined as  
150 *Self-difficult trials* evoking high cognitive dissonance), and the remaining one-half included  
151 one highly preferred food and one unpreferred food (rated below 3—these trials were defined  
152 as *Self-easy trials*, evoking low cognitive dissonance). In a control, *Computer trials*,  
153 participants were instructed to press the button corresponding to the food item randomly  
154 chosen by the computer (highlighted by a red square). Importantly, in *Computer trials*, items  
155 were programmed and selected with the same criteria used for *Self-difficult trials*. Overall,  
156 each food item appeared in only one pair. At the beginning of each trial, participants were  
157 informed about the trial type (*Self-trial* or *Computer trial*). Participants had 5 seconds to

158 make their choice or press the keyboard button corresponding to the computer’s choice. In  
159 case of no answer, a written message, “Please, respond faster,” appeared at the center of the  
160 screen.

161 During *Preference task II*, participants had to rate the same set of foods again. Unlike  
162 *Preference task I*, an additional text indicated either the participant’s or the computer’s  
163 decision during the *Choice task* (e.g., “you chose it,” “you rejected it,” or “computer chose  
164 it,” “computer rejected it”). Finally, participants attended an additional control condition—a  
165 *Post-ex choice* task (see Izuma et al., 2010, for details). Subjects were instructed to choose  
166 from the same pairs of foods that had appeared during the *Computer trials* of the *Choice task*  
167 *conditions*.

168 At the end of the experiment, we randomly selected one of the items that participants had  
169 selected during *Self-difficult trials* or *Post-ex choice trials* as an additional reward for the  
170 participants.

171

172 Figure 1

173

#### 174 *Eriksen flanker task*

175 At the end of the study, subjects performed the Eriksen flanker task. A string of 7 elements  
176 appeared on the monitor for 150 ms followed by a black screen (600–1000 ms). Each string  
177 consisted of a central element (the target) and 3 flankers. The elements were combined as  
178 *congruent* (<<<<<<<< or >>>>>>>) or *incongruent* (<<<<<<<< or >>>>>>>) stimuli.  
179 Participants were instructed to react as quickly and accurately as possible by pressing the  
180 correct button according to the orientation (left or right) of the target element, regardless of  
181 the orientation of the flankers. If participants responded too late (slower than 800 ms), a  
182 message, “you are too late,” prompted them to respond faster. The task consisted of 7 blocks  
183 (60 trials per block). Each string type appeared with a probability of 0.25.

#### 184 *Behavioral measure and analysis*

185 To assess the effect of cognitive dissonance on behavioral preference changes, or SoA, we  
186 calculated preference change by subtracting the average rating made during *Preference task*  
187 *II* minus from the average rating made during *Preference task I*, separately for the selected

188 and rejected items and the four experimental conditions (*Self-difficult* and *Self-easy trials*,  
189 *Computer choice*, and *Post-ex choice*). A positive preference change indicated an increased  
190 post-decisional preference for the food item (more liking), whereas a negative preference  
191 change suggested a decreased post-decisional preference for the food item (less liking). SoA  
192 (post-decisional preference change) analysis was performed by entering both accepted and  
193 rejected item ranks (*Preference task II* minus *Preference task I*) for each of the experimental  
194 conditions into paired *t*-tests (see Izuma et al., 2010, for a similar analysis) and two-way  
195 ANOVA.

## 196 ***Procedure***

### 197 *Resting-state recordings*

198 At the beginning of the study, subjects sat comfortably in a chair for 10 minutes with their  
199 eyes open while a resting-state recording was performed. Subjects were instructed to relax  
200 and not move during the recordings.

### 201 *ERP recordings*

202 The EEG data were collected for each subject during the whole experiment at the 500-Hz  
203 sampling rate in the frequency range 0.2–100 kHz from 60 high-impedance ActiCap active  
204 scalp electrodes (Brain Products, Gilching, Germany), which were positioned according to  
205 the international 10–20 system. Impedances were kept below 10 k $\Omega$ . Eye movements were  
206 recorded with Ag/AgCl electrodes placed at both lateral canthi and below the left eye. EEG  
207 signals were referenced to arithmetically link mastoids. Offline, the EEG was band-pass  
208 filtered in 0.1 - 30 Hz frequency range. The data were inspected for artifacts (amplitudes  
209 exceeding  $\pm 100$   $\mu$ V), and less than 10% of all trials in each condition and with each  
210 participant were rejected.

## 211 ***Data Analysis***

### 212 *Analysis of the resting-state recordings*

213 In the present study, we focused on the analysis of alpha oscillations in the resting state for  
214 two reasons. First, alpha oscillations have been shown to be involved in many cognitive  
215 operations, including memory, attention, and decision making (Cohen, Elger, & Fell, 2009;  
216 Jensen et al., 2002; Klimesch, 1999, 2012). Second, alpha oscillations have a large signal-to-  
217 noise ratio, which facilitates extraction of their amplitude without it being strongly affected

218 by muscle activity (Frey, Ruhnau, & Weisz, 2015; Klimesch, 2012; Palva, Palva, & Kaila,  
219 2005; Palva & Palva, 2007). For the extraction of the instantaneous amplitude, we used an  
220 analytic signal concept based on the Hilbert transform. Following a previously established  
221 practice (Hardstone et al. 2012), we extracted alpha oscillations in low 8–10-Hz and high 10–  
222 12-Hz frequency bands as well as in a broad 8–13-Hz range. Mean amplitude was calculated  
223 as the average of the instantaneous amplitude over 10 minutes of rest recordings.

224 Temporal dynamics of alpha oscillations were estimated with detrended fluctuation analysis  
225 (DFA) (Kantelhardt et al., 2001; Peng et al., 1995), which quantifies decay of the  
226 autocorrelation function. In general, the autocorrelation function shows how, in a given  
227 signal, events in the past relate to events in the future. If there is very little “memory” in the  
228 signal, the autocorrelation quickly and exponentially decays. However, many recent  
229 EEG/MEG studies (for a review, see Hardstone et al., 2012) have shown that the amplitude  
230 envelope of resting-state neuronal oscillations demonstrate a very slow decay of  
231 autocorrelations, hence the label—LRTC.

232 Algorithmically, DFA captures fluctuations of the signal at different time scales, and the  
233 slope of the corresponding line is called a scaling exponent. For random signals such as white  
234 noise, the scaling exponent is 0.5. However, if there are persistent LRTC, the exponent will  
235 lie in the 0.5–1 range. Higher scaling exponents correspond to more pronounced LRTC.

236 For DFA, we used 30 time windows, from 5 to 50 seconds, distributed equidistantly on a  
237 logarithmic scale. Further technical details on the application of DFA for the estimation of  
238 LRTC in EEG/MEG signals can be found in Hardstone et al. 2012. We then correlated  
239 scaling exponents and the amplitude of the oscillations with the SoA effect in the *Self-easy*  
240 and *Self-difficult trials*, as well as with the amplitude of evoked responses in the free-choice  
241 paradigm. For the behavioral data, we used a region-of-interest (ROI) approach and averaged  
242 LRTC scaling exponents in the electrodes belonging to the fronto-central area (F1, F2, F3,  
243 F4, Fz, FCz) where ERN was most pronounced. Consequently, we correlated this ROI  
244 scaling exponent with the behavioral data. Scaling exponents and amplitudes from this ROI  
245 were correlated with the SoA. For the evoked responses, we selected amplitudes from the  
246 FCz electrode and then correlated them with the scaling exponents and amplitude of alpha  
247 oscillations obtained from all electrodes. In this case, since we had calculations of multiple  
248 correlations, we applied permutation tests based on cluster statistics (Maris & Oostenveld,

249 2007). All analytical steps were performed with scripts implemented in Matlab (The  
250 MathWorks Inc., Natick, Massachusetts, USA).

### 251 *Analysis of ERP*

252 We analyzed response-locked activity in both tasks. In the free-choice paradigm, the  
253 response-locked ERPs elicited during *Self-difficult trials* and *Self-easy trials* were subjected  
254 to an analysis of the effect of cognitive dissonance. To examine ERN, in the Eriksen flanker  
255 task we calculated the difference between the average response-locked ERPs in trials with  
256 both incorrect responses and correct responses.

257 Additionally, a paired *t*-test was performed for the FCz electrode based on the individually  
258 averaged ERP responses at the latency window between 0 and 90 ms from the response onset  
259 and a 35-ms integration window. A significance of the differences between the conditions  
260 was assessed with permutation tests based on cluster statistics (Maris & Oostenveld, 2007).  
261 We compared response-locked ERPs in *Self-difficult trials* to response-locked ERPs in *Self-*  
262 *easy trials* in the free-choice paradigm. We also compared response-locked ERPs in incorrect  
263 responses to response-locked ERPs in correct responses in the Eriksen flanker task.

### 264 *Source localization analysis*

265 We used the low-resolution brain electromagnetic tomography (LORETA) method—  
266 implemented in the Brain Vision Analyzer (Brain Products GmbH, Germany)—to identify  
267 the neural generator of the ERN and cognitive dissonance-related ERPs. LORETA estimates  
268 the current source density distribution in the brain, which contributes to the electrical scalp  
269 field (Pascual-Leone, Bartres-Faz, & Keenan, 1999; Pascual-Marqui, Michel, & Lehmann,  
270 1994). LORETA computes the smoothest of all possible source configurations throughout the  
271 brain volume by minimizing the total squared Laplacian of source strengths (Pascual-Marqui,  
272 2002; Pascual-Marqui et al., 1994; Schneider et al., 2009). Here, we employed LORETA to  
273 identify the neural generator of the ERN and cognitive dissonance-related ERPs recorded in  
274 the Eriksen flanker task and the free-choice paradigm.

## 275 **Results**

### 276 *Behavioral correlates of post-decisional preference change*

277 Since strong cognitive dissonance should occur during difficult decisions (*Self-difficult trials*  
278 and *Post-ex choice*), we predicted that the magnitude of the SoA should be enhanced as a

279 function of choice difficulty. Thus, we expected a larger SoA for *Self-difficult* and *Post-ex*  
280 *choice trials* than for *Self-easy* and *Computer trials* (Figure 2).

281 SoA analysis was subjected to a two-way (factor *trial type*: *Self-difficult*, *Self-easy*, *Computer*  
282 *trials*, and *Post-ex choice*; factor *choice*: selected versus rejected) repeated measure within-  
283 subject ANOVA. We found a main effect of *trial type* ( $F(3,123) = 57.488, p < 0.001$ ) and  
284 *choice* ( $F(1,41) = 45.43, p < 0.001$ ). The ANOVA also revealed a significant interaction  
285 between *trial type*  $\times$  *choice*:  $F(3,123) = 105, p < 0.001$ . As predicted, we observed a  
286 significantly larger SoA for rejected items in *Self-difficult trials* than for rejected items in  
287 *Self-easy trials*.

288 We also analyzed the SoA in trials with the highest cognitive dissonance: *Self-difficult trials*  
289 and control *Post-ex choice* trials. A two-way (factor *trial type*: *Self-difficult*, *Post-ex choice*;  
290 factor *choice*: selected, rejected) repeated measure within-subject ANOVA showed a  
291 significant main effect of *choice* ( $F(1,41) = 202.92, p < 0.001$ ) but not *trial type* ( $F(1,41) < 1,$   
292  $p = 0.770$ ). Crucially, we found significant interaction between *trial type*  $\times$  *choice* ( $F(1,41) =$   
293  $7.43, p = 0.009$ ), indicating a larger SoA for *Self-difficult trials* than for *Post-ex choice* trials.

294 Post-hoc analyses revealed that participants' preferences for items that were rejected during  
295 *Self-difficult trials* significantly decreased compared to both the rejected items in *Self-easy*  
296 *trials* ( $t(41) = -11.090, p < 0.001$ ) and the selected items in *Self-difficult trials* ( $t(41) = -$   
297  $12.005, p < 0.001$ ). The SoA for items that were rejected during *Self-difficult trials* was  
298 significantly stronger than it was for items rejected or selected in the control *Computer trials*:  
299  $t(41) = -7.143, p < 0.001$  and  $t(41) = -7.263, p < 0.001$ , respectively.

300 The SoA of rejected items in *Self-difficult trials* approached significance when compared to  
301 rejected items in another control *Post-ex choice* condition:  $t(41) = -1.779, p = 0.083$ . Note,  
302 however, that all of the remaining comparisons showed a significant effect (all  $p < 0.001$ )  
303 except for the SoA between accepted and rejected items in *Computer trials* ( $t(41) = -1.402, p$   
304  $= 0.168$ ).

305 To conclude, our results replicate previous SoA findings using the free-choice paradigm  
306 (Izuma et al., 2010; Salti et al., 2014). Importantly, the efficiency of the control conditions for  
307 the free-choice paradigm is still debated (Coppin et al., 2014) and further investigation is  
308 needed. Therefore, the electrophysiological signature of cognitive dissonance during control  
309 conditions is not discussed in this paper.

310 Overall, our results showed that (1) participants de-evaluated previously rejected items (SoA  
311 effect) and (2) the SoA effect for rejected items was stronger for more difficult choices  
312 associated with stronger cognitive dissonance.

313

314 Figure 2

315

### 316 *ERN in the Eriksen flanker task*

317 During the control Eriksen flanker task, error responses were followed by larger fronto-  
318 central negativity—ERN—when compared with correct responses approximately 60 ms after  
319 the button press. Previous studies have indicated the maximum of ERN at FCz (Yeung,  
320 Botvinick, & Cohen, 2004). Therefore, we conducted a paired *t*-test that showed a significant  
321 difference between *error responses* and *correct responses* at FCz:  $t(20) = -5.57, p = 0.001, d$   
322  $= 1.2$ . The ERN's time course and topographical map are illustrated in Figure 3A.

323 To localize the generator of the ERN, we applied LORETA transformation to the evoked  
324 activity within a preselected time window corresponding to  $\pm 10$  ms around the grand-  
325 averaged maximum peak for difference waves (*error responses* minus *correct responses*).

326 As expected, LORETA analysis highlighted a prominent activation of the pMFC, with the  
327 strongest activity in the BA6 (See Table 1 for XYZ and BA coordinates); this finding is  
328 similar to previous studies that investigated the ERN generator in the Eriksen flanker task  
329 (Herrmann et al., 2004).

### 330 *ERP correlates of cognitive dissonance*

331 Initially, we analyzed cognitive dissonance-related activity in fronto-central sites—FCz, Cz,  
332 and Fz—that often demonstrate the largest ERN. Indeed, we found that the largest cognitive  
333 dissonance-related activity was observed in FCz. Figure 3B shows the grand-averaged ERPs  
334 and the difference wave at the fronto-central midline electrode FCz, as well as a  
335 topographical map of the voltage distribution for the difference wave (*Self-difficult* minus  
336 *Self-easy trials*). A *t*-test for the mean ERP amplitude (*Self-difficult trials* versus *Self-easy*  
337 *trials*, FCz, time window = 36 ms) revealed a significant effect of cognitive dissonance:  $t(41)$   
338  $= -2.190, p = 0.032$ . The *Self-difficult trials* (associated with stronger cognitive dissonance)

339 evoked a significantly larger negative fronto-central deflection at a latency of 46 ms than the  
340 *Self-easy trials*.

341 For a more conservative analysis of the differential ERPs (*Self-difficult trials* versus *Self-easy*  
342 *trials*), we applied paired *t*-tests with a permutation procedure based on cluster statistics  
343 (Maris & Oostenveld, 2007). We found a cluster of electrodes that survived a 200-random-  
344 iteration permutation procedure (Figure 3B, represented by magenta crosses). The analysis  
345 showed that the cluster of 17 temporal and fronto-central electrodes showed significant  
346 difference according to the permutation procedure.

347 Similar to the Eriksen flanker task, we applied the LORETA transform to explore the source  
348 generator of cognitive dissonance-related activity. The LORETA time window's parameters  
349 matched those of the flanker task ( $\pm 11$  ms around the grand-averaged maximum peak for  
350 *Self-difficult trials*, *Self-easy trials*, and difference waves). As Figure 3A shows, sources of  
351 the difference wave were localized in the occipital cortex, ventral prefrontal cortex, and the  
352 pMFC, with the greatest activity occurring within the BA6. Overall, the fronto-central  
353 distribution of cognitive dissonance-related evoked activity in the free-choice paradigm and  
354 its pMFC origin (Figure 3B) were very similar to the fronto-central distribution of ERN in the  
355 standard flanker task (Figure 3A).

### 356 *Relationship between ERP correlates of cognitive dissonance and post-decisional preference* 357 *changes (SoA)*

358 To examine the relationship between the magnitude of the ERN-like correlates of cognitive  
359 dissonance and post-decisional preference changes, we investigated the relationship between  
360 the aforementioned evoked activity and individual preference changes for rejected items. We  
361 calculated the Pearson correlation analysis (Figure 4) for the difference waves (*Self-difficult*  
362 *trials* minus *Self-easy trials* at three midline electrodes: FCz, Fz, and Cz) and SoA effects for  
363 rejected items (in *Self-difficult trials*): We found a trend of significant positive correlation at  
364 both the FCz ( $r = 0.208$ ,  $p = 0.093$ ) and Cz ( $r = 0.280$ ,  $p = 0.036$ ) electrodes. Thus, the  
365 stronger ERN-like correlates of cognitive dissonance were observed (*Choice task*) and the  
366 stronger individual preferences were later changed for rejected items (*Preference task II*).

367

368 Figure 3

369 Figure 4

370

Table 1

371

372 *Resting-state neuronal dynamics predict post-decisional preference changes (SoA) and the*  
373 *amplitude of the ERP correlates of cognitive dissonance*

374 We correlated the individual magnitude of SoA with the LRTC scaling exponents that  
375 described dynamics of alpha oscillations recorded during rest at the beginning of the  
376 experiment. We found a significant negative correlation ( $r = -0.37, p = 0.02$ ) between LRTC  
377 scaling exponents (8–13 Hz) at the frontal ROI (see Materials & Methods) and the SoA for  
378 rejected items in *Self-difficult trials*. This correlation indicates that the more pronounced  
379 frontal LRTC at the rest predicts a stronger decrease in preference for the rejected items in  
380 *Self-difficult trials* later on.

381 Since evoked responses at the FCz electrode showed the most significant difference between  
382 *Self-easy* and *Self-difficult trials*, we correlated amplitude measures from this electrode with  
383 LRTC scaling exponents and the amplitude of alpha oscillations recorded at rest. Our analysis  
384 showed that LRTC scaling components (8–10 Hz band) were correlated negatively ( $p < 0.05$ )  
385 with the cognitive dissonance-related difference wave (*Self-difficult trials* minus *Self-easy*  
386 *trials*). Figure 5B shows a topography of this correlation. The significant cluster is widely  
387 distributed, covering the frontal and central part of the head. The amplitude of the alpha  
388 oscillations recorded during rest did not correlate with the evoked responses (Figure 6C).  
389 Overall, our findings indicate that a more pronounced LRTC lead to larger ERP and  
390 behavioral correlates of post-decisional adjustments of preferences.

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Figure 5

393

394 **Discussion**

395 Similar to previous studies (Brehm, 1956; Izuma et al., 2010; Kitayama et al., 2004;  
396 Mengarelli et al., 2015; van Veen et al., 2009), our behavioral results demonstrate that  
397 decisions induce preference changes: Individuals were more likely to downgrade their  
398 preferences for rejected items in order to align them with their actual choices.

399 A previous neuroimaging study (Izuma et al., 2010) showed the neural signature of choice-  
400 induced preference change during the re-rating of options—the paradigm which was also  
401 utilized in our study. The authors found that the pMFC activity reflected the degree of  
402 cognitive dissonance and predicted the strength of choice-induced preference changes.  
403 Moreover, a recent transcranial magnetic stimulation (TMS) study demonstrated a causal role  
404 for the pMFC in choice-induced preference change: Repetitive TMS of the pMFC following  
405 the choice stage significantly reduced choice-induced preference changes compared with  
406 control stimulations over a different brain region (Izuma et al., 2015). Therefore, Izuma  
407 (2013) concluded that the activity of the pMFC reflects internal consistency between one’s  
408 opinions and behaviors and associated cognitive dissonance with the processes underlying  
409 changes in opinions and behaviors.

410 Although cognitive dissonance has traditionally been investigated using the free-choice  
411 paradigm (Brehm, 1956; Harmon-Jones & Harmon-Jones, 2007), little is known about the  
412 cognitive and neural processes that occur during the decisional stage nor their role in follow-  
413 up post-decisional preference changes.

414 To the best of our knowledge, the present study is the first EEG study to directly investigate  
415 neural correlates of cognitive dissonance during the decisional process. Our ERP data suggest  
416 that choices associated with stronger cognitive dissonance trigger a greater negative fronto-  
417 central ERN-like deflection with the maximum at 60 ms (after the choice). Importantly, the  
418 timing and localization of the observed cognitive dissonance-related ERP was very similar to  
419 ERN, which has often been implicated in performance monitoring and signaling of negative  
420 reward prediction error (Gehring & Willoughby, 2002; Holroyd & Coles, 2002; Miltner,  
421 Braun, & Coles, 1997; Nieuwenhuis et al., 2004; Nieuwenhuis et al., 2007). Furthermore,  
422 amplitudes of ERN-like potentials predicted individual differences in post-decisional  
423 preference changes: A larger ERN-like potential was associated with larger preference  
424 changes.

425 In the control study, we recorded the standard ERN during the flanker task (Falkenstein et al.,  
426 1995; Gehring et al., 2011; Holroyd & Coles, 2002) in order to test the spatial and temporal  
427 correspondence of the ERN-like potential generated during the free-choice paradigm with  
428 standard ERN. Our results show a strong similarity between the spatial and temporal  
429 characteristics of both evoked responses. A difference in the amplitudes of the Eriksen  
430 flanker task and ERN-like potential in the free-choice paradigm may be due to difference in

431 task difficulty. Since the Eriksen flanker task is simpler than the free-choice paradigm, a  
432 smaller ERN-like potential could reflect more complex and slower mechanisms underlying  
433 relatively complex decisions during food choices. Previous studies demonstrated that ERN is  
434 indeed susceptible to changes in error salience or attention (Hajcak et al., 2005; Riesel et al.,  
435 2012).

436 The recent transcranial magnetic stimulation study demonstrated a causal role of the pMFC in  
437 post-decisional preference changes (Izuma et al., 2015). Off-line down-regulation of the right  
438 pMFC just after the *Choice task* induced a reduction of choice-induced preference changes  
439 (SoA). Importantly, our ERP study suggests that an earlier neural process might also be  
440 involved in the subsequent preference changes for rejected items. Our results indicate that  
441 during choices associated with strong cognitive dissonance, the pMFC is already generating a  
442 neural error-signal reflecting the need for behavioral adjustments similar to ERN.

443 Furthermore, the critical role of the pMFC in cognitive dissonance and choice-induced  
444 preference changes (Izuma et al., 2010) suggests that its ongoing, spontaneous (resting state)  
445 activity may affect follow-up neural and behavioral effects of cognitive dissonance. For the  
446 quantification of spontaneous oscillatory dynamics, we used LRTC, which captures neuronal  
447 activity at different time scales. The presence of LRTC is consistent with the idea that  
448 neuronal networks might operate at a critical meta-stable state (Linkenkaer-Hansen et al.,  
449 2001; Poil et al., 2012) that could be beneficial for the optimal processing of information in  
450 the brain (Shew & Plenz, 2013). For example, recent studies have shown that the perception  
451 of near-threshold sensory stimuli (Palva et al., 2013) and the precision in sensorimotor tasks  
452 (Smit et al., 2013; Samek et al., 2016) are related to the LRTC of neuronal oscillations  
453 recorded at rest. Thus, LRTC studies robustly demonstrate that specific synaptic  
454 configurations within specific brain regions uniquely define behavioral performance. We  
455 went a step further and demonstrated that LRTC at rest are also associated with more  
456 complex cognitive processes, such as cognitive dissonance-induced preference changes, or  
457 SoA effects. Thus, the SoA-related reconfiguration of neuronal value representations might  
458 require efficient rerouting of synaptic inputs and their consecutive stabilization: processes  
459 best implemented by the delicate balance of excitation and inhibition within specialized  
460 neural microcircuitry (Rolls et al., 2008).

461 Importantly, LRTC are in fact most pronounced when excitation and inhibition are balanced  
462 (Poil et al., 2012). Thus, individuals with stronger LRTC at frontal cortices might

463 demonstrate a larger SoA, which was indeed observed in the present study. Interestingly, we  
464 also found that LRTC in frontal areas predicted not only behavioral outcomes of the follow-  
465 up free-choice paradigm but were also correlated with the evoked brain responses when  
466 choosing between two items. This finding is in line with the general conception that LRTC of  
467 alpha oscillations, recorded at rest, are likely to reflect large-scale cortical excitability (Fedele  
468 et al., 2016) and could therefore also be related to the generation of ERP.

469 Taken together, our electrophysiological results suggest that pMFC activity might play a  
470 critical role in modulating post-decisional preference changes occurring when difficult  
471 decisions between similarly attractive options are faced. Although previous studies found  
472 similar activity in the late stages of the decisional process in the free-choice paradigm  
473 (*Preference task II*), our data favor a central role of the pMFC in cognitive dissonance  
474 detection during the decisional process (*Choice task*). In fact, our study demonstrates that  
475 difficult decisions (high cognitive dissonance) trigger a more prominent ERN-like neural  
476 signal than easy decisions. ERN has been thought to reflect error detection (Luu et al., 2004),  
477 conflict detection, conflict monitoring (Yeung et al., 2004), and cognitive control  
478 (Ridderinkhof et al., 2004), as well as serving as an important electrophysiological correlate  
479 of reinforcement-learning mechanisms (Holroyd & Coles, 2002). The existence of ERN has  
480 been proven in a large set of experimental designs and paradigms, such as the Stroop task and  
481 flanker task. In our experiment, we found similar fronto-central activity during the free-  
482 choice paradigm and flanker task. Thus, our ERP data support the hypotheses that (1) pMFC  
483 activity during the decisional process plays a key role in preference modulation and (2) neural  
484 mechanisms of choice-induced preference changes might be similar to more general  
485 reinforcement-learning mechanisms.

486 Interestingly, some studies have shown that the left dorso-lateral prefrontal cortex (DLPFC)  
487 is also involved in cognitive dissonance (Harmon-Jones & Harmon-Jones, 2008; Harmon-  
488 Jones et al., 2011; Mengarelli et al., 2015). As the DLPFC has been shown to be implicated in  
489 cognitive control (Miller & Cohen, 2001), it was suggested that the DLPFC is not directly  
490 involved in cognitive inconsistency reduction; rather, its activity is believed to be related to a  
491 more general cognitive control process (Izuma et al., 2015) and the implementation of  
492 performance adjustment (Ridderinkhof et al., 2004). As in Ridderinkhof et al. (2004), the  
493 DLPFC and pMFC might have a functional interaction that permits the monitoring and  
494 execution of performance adjustment. Further studies are clearly needed to fully uncover *how*

495 the activity of the pMFC modulates subsequent preference changes as well as the role of the  
496 pMFC–DLPFC network in cognitive dissonance reduction.

497 In conclusion, our results provide strong evidence that post-decisional preference changes  
498 and performance monitoring demonstrate similar neural signatures. Choice-induced  
499 preference changes are reflected in the choice-related activity of the pMFC as part of the  
500 general performance-monitoring circuitry. Furthermore, resting-state dynamics determine  
501 both behavioral and neural correlates of post-decisional preference changes. Thus,  
502 neurocomputational mechanisms of choice- and feedback-induced preference changes may  
503 be more strongly intertwined than previously thought.

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712 **Captions**

713 **Figure 1.** Free choice paradigm. I. During *Preference task I* participants rated food items  
714 presented for 3 s on the screen. II. Next during *Choice task* in *Self trials*, subjects freely  
715 selected one of two food items (*Self-difficult trials* evoked strong cognitive dissonance, *Self-*  
716 *easy trials* evoked weak cognitive dissonance), while in *Computer trials*, subjects had to  
717 select the item that has been selected by the computational algorithm (highlighted by a red  
718 square). III. In *Preference task II* participants rated the same food items again. Participants  
719 were reminded about their choices (if any) during the Choice task, e.g., “You rejected it”. IV.  
720 Finally during control *Post-ex choice task* participants choose items from pairs that had been  
721 presented during *Computer trials*.

722 **Figure 2.** Post-decisional preference changes for selected and rejected items in free choice  
723 paradigm. Black lines below the histogram indicate statistically significant postdecisional  
724 preference change between *Preference task I* and *Preference Task II* for rejected items. Black  
725 lines:  $p < 0.001$ ; gray line:  $p = 0.083$ . Error bars indicate the standard error of the mean.

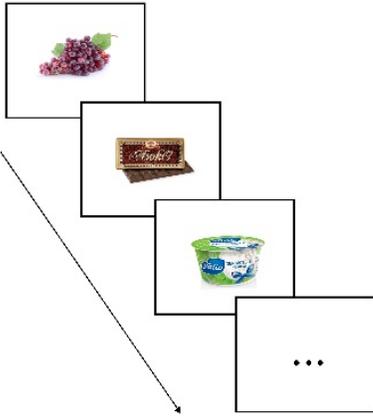
726 **Figure 3.** A. (Left) Grand-averaged ERN (FCz) for correct responses, incorrect responses and  
727 difference wave in the Eriksen Flanker task. (Right) Topographical map for difference wave  
728 voltage distribution and LORETA solutions (scale range: 0 – 0.01  $\mu\text{A}/\text{mm}^2$ ) for the difference  
729 wave within selected time window ( $\pm 11$  ms around the peak). B. (Left) Grand-averaged ERPs  
730 (FCz) for *Self-difficult trials*, *Self-easy trials* and difference wave, in the Free-choice  
731 paradigm. (Right) topographical map for voltage distribution of the difference wave and  
732 LORETA solutions (scale range: 0 – 0.005  $\mu\text{A}/\text{mm}^2$ ) within 36 ms time window. Magenta  
733 crosses represent electrodes surviving a 200 random iterations permutation procedure. In both  
734 voltage distribution maps FCz electrode is indicated by a large cross. All ERPs are response-  
735 locked.

736 **Figure 4.** Relationships between cognitive dissonance-related difference wave (maximum  
737 voltage at Fz – left column, FCz – central column and Cz – right column) and the SoA  
738 magnitude for rejected items in *Self-difficult trials*.

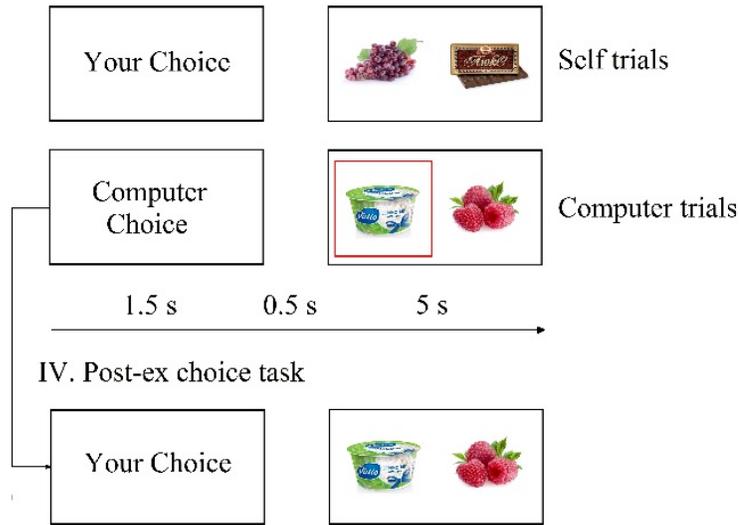
739 **Figure 5.** A. A relationship between LRTC scaling exponents and SoA magnitude for the  
740 rejected items in *Self-difficult trials*. B. Topography of the correlation between LRTC scaling  
741 exponents and the amplitude of the difference wave (*Self-easy* minus *Self-difficult trials*).  
742 Cross indicates electrodes belonging to a significant cluster. C. A scatter-plot showing a  
743 relation between the LRTC scaling exponents (FC2 electrode) and the amplitude of the  
744 difference wave (*Self-difficult* minus *Self-easy trials*) at FCz electrode. The red line depicts  
745 the linear least-squares fit.

746 **Table 1.** \*BA=Brodman Area; X, Y, Z, coordinates in Talairach space in mm; Z corresponds  
747 to the cranial–caudal, X to the left–right and Y to the anterior–posterior dimension.

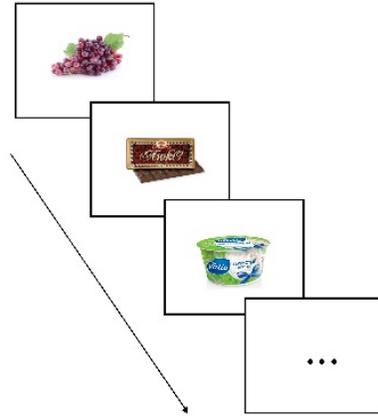
I. Preference task 1

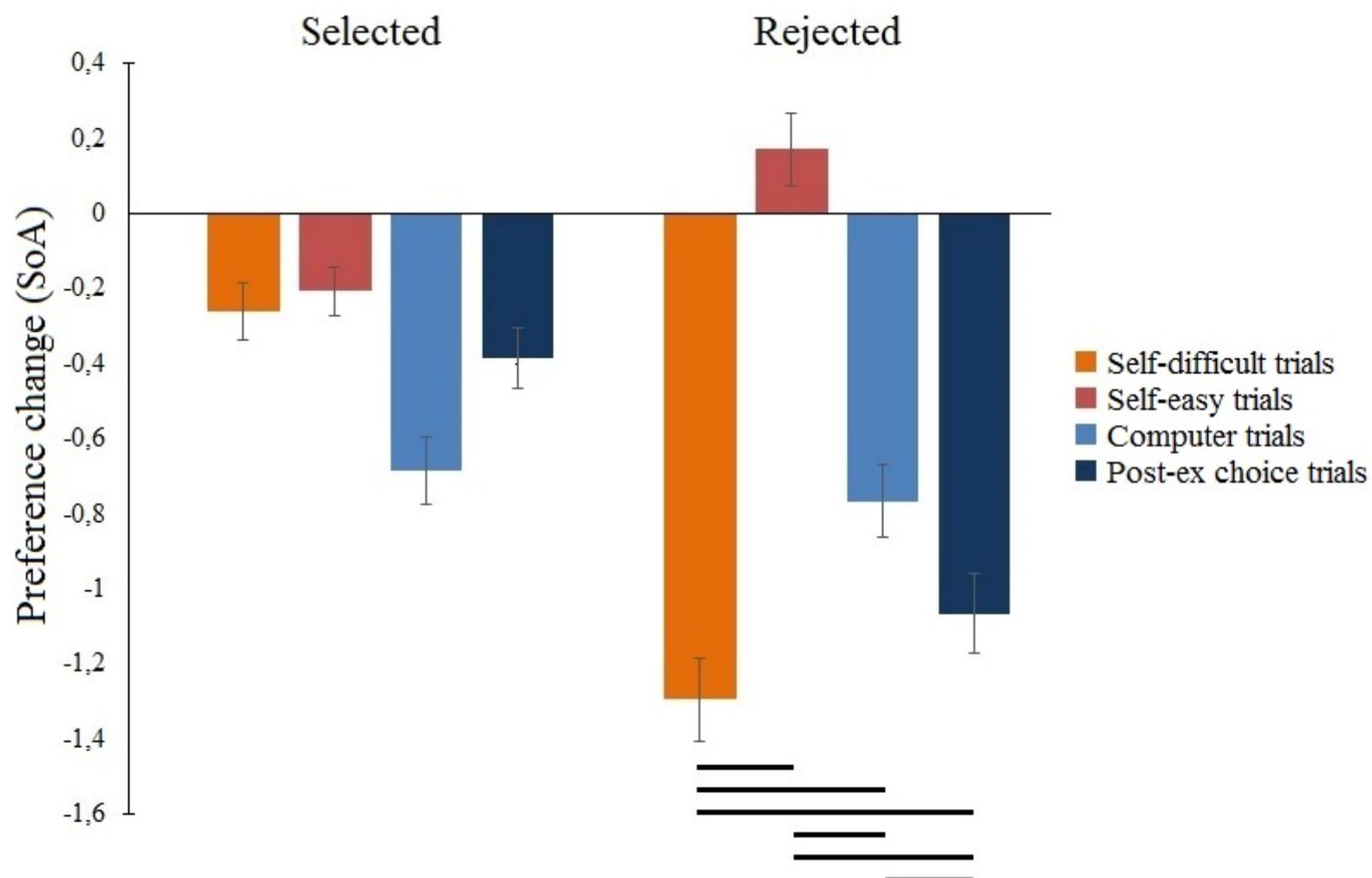


II. Choice task

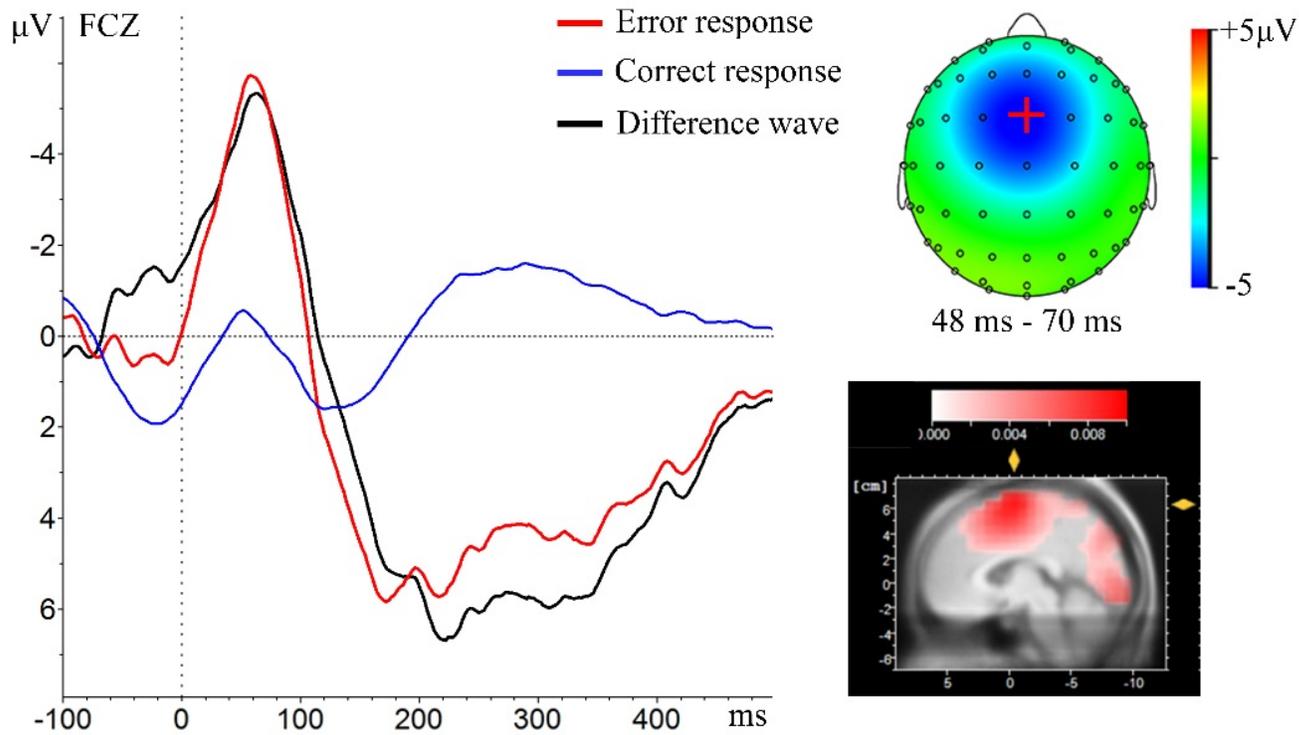


III. Preference task 2

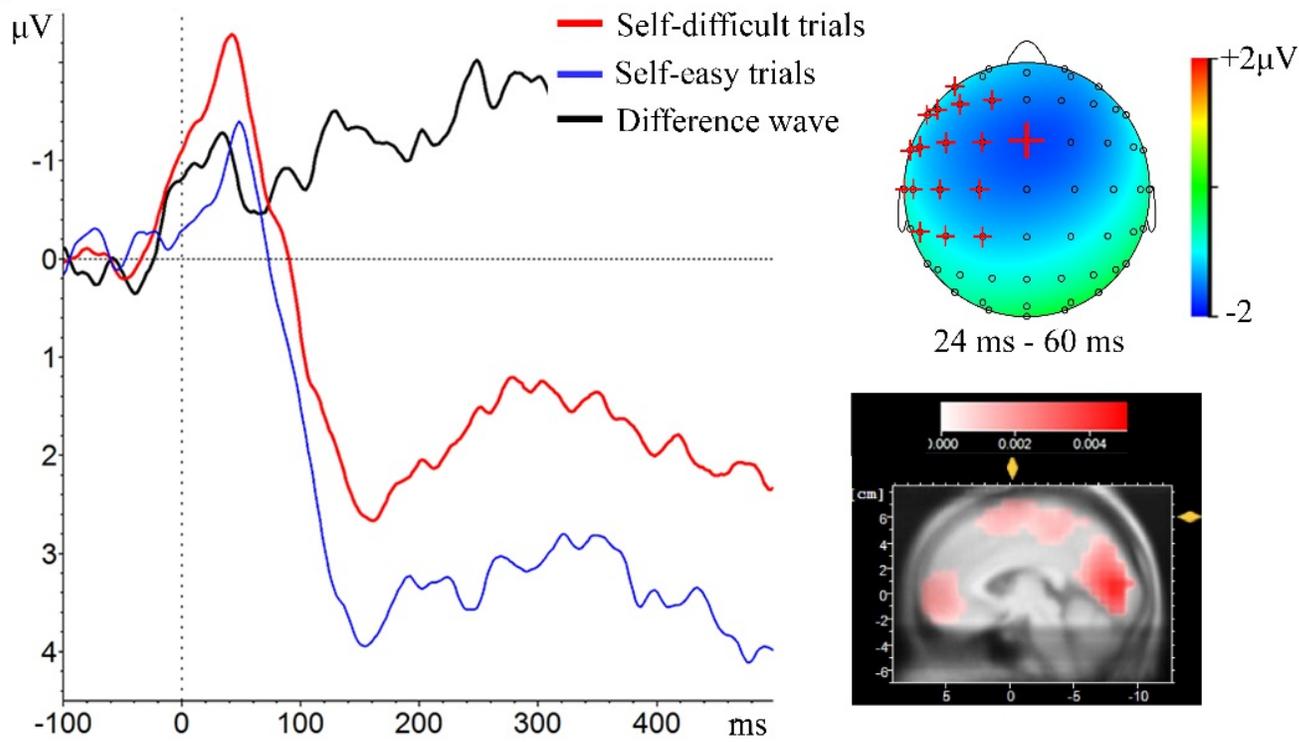


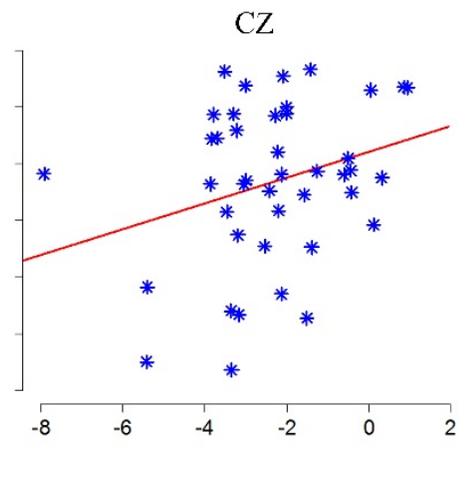
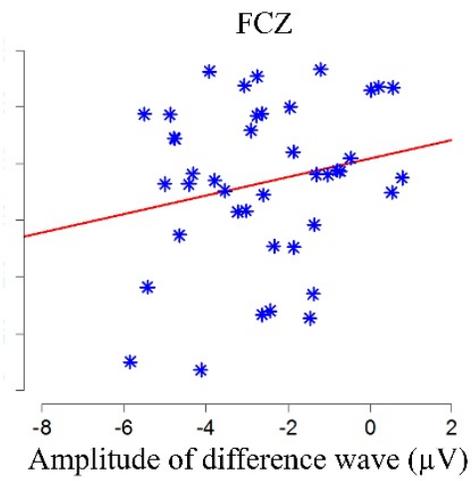
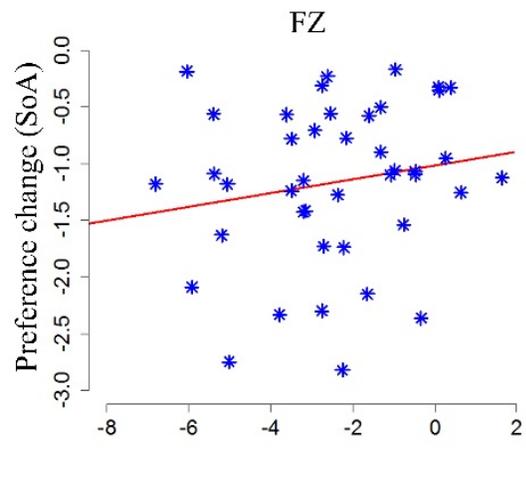


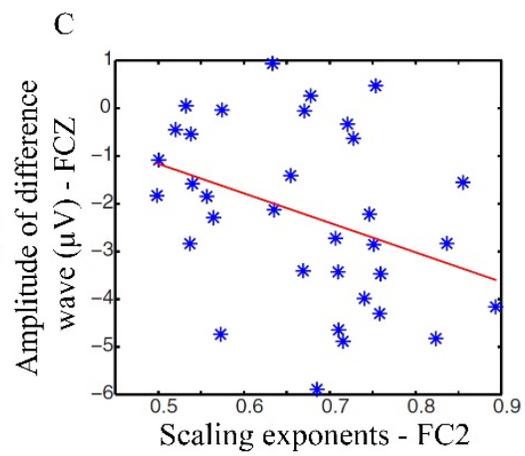
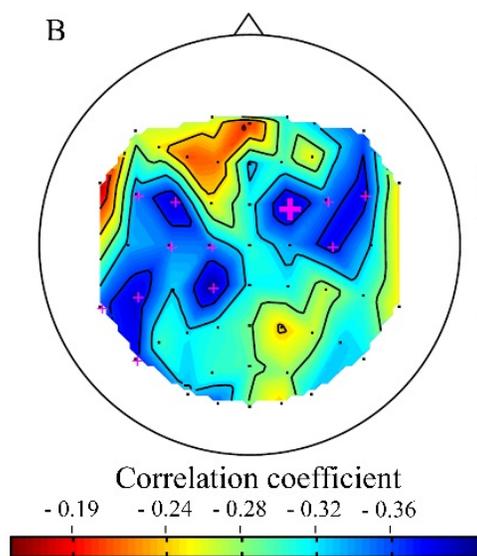
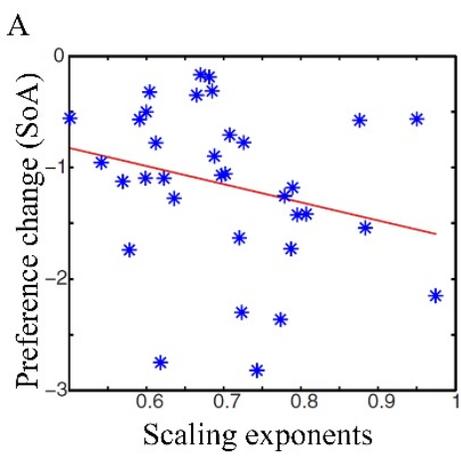
A



B







## Table

**Table 1.** LORETA solutions - Localization of the CD/Error-related ERPs at the pMFC in Free-choice Paradigm and Eriksen Flanker Task.

| Condition        | X  | Y   | Z  | BA* | Task                 |
|------------------|----|-----|----|-----|----------------------|
| Self-Difficult   | -3 | -4  | 64 | 6   | Free-choice Paradigm |
| Self-Easy        | -3 | -11 | 64 | 6   | Free-choice Paradigm |
| Difference Wave  | 4  | -2  | 61 | 6   | Free-choice Paradigm |
| Incorrect trials | -3 | -4  | 64 | 6   | Flanker Task         |
| Correct trials   | 4  | -3  | 66 | 6   | Flanker Task         |
| Difference Wave  | -3 | -4  | 64 | 6   | Flanker Task         |