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The temporal dynamics of metacognition:

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Dissociating task-related activity from later metacognitive processes

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Abstract

26 In recent years, neuroscience research spent much effort in revealing brain activity related to
27 metacognition. Despite this endeavor, it remains unclear exactly when metacognitive experiences
28 develop during task performance. To investigate this, the current study used EEG to temporally and
29 spatially dissociate task-related activity from metacognitive activity. In a masked priming paradigm,
30 metacognitive experiences of difficulty were induced by manipulating congruency between prime and
31 target. As expected, participants more frequently rated incongruent trials as difficult and congruent
32 trials as easy, while being completely unable to perceive the masked primes. Results showed that
33 both the N2 and the P3 ERP components were modulated by congruency, but that only the P3
34 modulation interacted with metacognitive experiences. Single-trial analysis additionally showed that
35 the magnitude of the P3 modulation by congruency accurately predicted the metacognitive response.
36 Source localization indicated that the N2 task-related activity originated in the ACC, whereas the P3-
37 interplay between task-related activation and metacognitive experiences originated from the
38 precuneus. We conclude that task-related activity can be dissociated from later metacognitive
39 processing.

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41 **Keywords: response conflict, metacognition, N2/P3, precuneus, ACC, EEG**

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Introduction

44 When acting upon stimuli in the environment, our actions are accompanied by metacognitive
45 experiences. For example, when typing on a foreign keyboard, you will clearly experience that your
46 actions do not proceed very fluently. While the neurocognitive underpinnings of metacognition have
47 recently received a lot of attention (Fleming, Ryu, Golfinos, & Blackmon, 2014; Fleming, Weil, Nagy,
48 Dolan, & Rees, 2010; McCurdy et al., 2013), it remains unclear how these metacognitive experiences
49 develop in time. For example, it is highly debated whether metacognitive experiences associated
50 with our actions are created at the same time of the decision to act, or whether they also depend on
51 new information arriving beyond this decision point (Yeung & Summerfield, 2012). More generally, it
52 is unknown at which point in time specific neural processes contribute to the creation of
53 metacognitive experiences.

54 Metacognition, a general term used to describe the subjective experiences associated with
55 our actions, has been studied in a variety of research fields. In the meta-memory literature,
56 researchers have extensively investigated subjective experiences associated with memory formation,
57 such as judgments-of-learning during acquisition (Metcalf & Finn, 2008), and feeling-of-knowing
58 during recall (e.g., Díaz, Lindín, Galdo-Alvarez, Facal, & Juncos-Rabadán, 2007). In the neurocognitive
59 literature, most studies use low-level perceptual decision tasks, and examine the degree of
60 confidence associated with decisions (de Gardelle & Mamassian, 2014; Fleming & Lau, 2014; Fleming
61 et al., 2010) or the awareness of having made an error in the decision process (Boldt & Yeung, 2015;
62 Steinhäuser & Yeung, 2010). In the current study, we focus on one particular class of metacognitive
63 experiences, namely the experience of fluency in action-selection. Several recent studies already
64 demonstrated that participants can reliably introspect on the fluency of their action-selection, even
65 when they are unaware of the stimuli manipulating the fluency of selection. For example, Charles et
66 al. (2013) showed that participants could differentiate between correct and incorrect judgments in a
67 simple decision task, even though they did not perceive the stimulus they had to decide on. In a
68 similar vein, studies have used subliminal priming to create a conflict between two responses, and
69 observed that task performance and perceived difficulty were jointly influenced, without participants
70 being aware of the visual stimuli driving these changes (Chambon & Haggard, 2012; Desender, Van
71 Opstal, & Van den Bussche, 2014; Wenke, Fleming, & Haggard, 2010). That is, even though
72 participants are completely unaware of the presence of the subliminal stimuli creating the response
73 conflict, they nevertheless have the metacognitive experience that responding was more difficult on
74 those trials where the subliminal stimulus interfered with response selection. A major benefit of
75 these conflict paradigms is that a large body of research has already documented the neural
76 components associated with the processing of response conflicts. However, while it was recently
77 demonstrated that metacognitive experiences are critically involved in conflict processing (Desender
78 et al., 2014), the role of metacognitive experiences in relation to these components has not been
79 studied.

80 Conflict tasks are known to reliably modulate two important event-related components
81 (ERPs) in the EEG waveform (Ullsperger, Fischer, Nigbur, & Endrass, 2014). First, a fronto-central N2
82 component around 200 - 300 ms post-stimulus is observed, which is believed to reflect a sensitivity
83 of the anterior cingulate cortex (ACC) to the activation of incompatible responses (Van Veen & Carter,
84 2002). Later in time, a central-parietal P3 component around 300 - 400 ms post-stimulus emerges,
85 whose functional role is still a matter of debate. Some consider it to be an index of stimulus

86 evaluation (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Purmann, Badde, Luna-Rodriguez, &
87 Wendt, 2011), whereas others assume that the P3 reflects the engagement of attentional resources
88 needed for improved control (Clayson & Larson, 2011; West, 2003). Interestingly, the P3 component
89 is also considered as a signature for conscious access (Del Cul, Baillet, & Dehaene, 2007; Kouider et
90 al., 2013), making it a likely neural correlate of metacognitive awareness in conflict tasks.

91 Based on existing evidence, both the N2 and P3 could be involved in metacognition. First,
92 noting that activity in the ACC is related to both cognitive (e.g., response conflict, errors) and
93 affective (e.g., pain) factors, Spunt and colleagues (2012) showed that the ACC tracks changes in
94 subjective experience, such as frustration and negative affect (for theoretical perspectives, see e.g.,
95 Hillman & Bilkey, 2013; Shackman et al., 2011). Therefore, metacognition could be related to activity
96 in the ACC, reflected by the N2 component. Second, research on error processing revealed that
97 awareness of one's own errors selectively modulates the error positivity (Pe) around 300 ms post-
98 response (Hughes & Yeung, 2011; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001), whereas
99 the earlier error related negativity (ERN; originating from the ACC; Yeung, Botvinick, & Cohen, 2004)
100 is only modulated by objective accuracy (although this latter claim has been contested, see e.g.,
101 Scheffers & Coles, 2000; Shalgi & Deouell, 2012; Wessel, 2012). Given that the Pe is considered to be
102 the error-related homologue of the P3 (Ridderinkhof, Ramautar, & Wijnen, 2009), metacognition
103 should be expressed in the P3 component only.

104 In short, while both the N2 and the P3 could theoretically be linked to metacognitive
105 experiences, this has not been tested before. The aim of the current study is to investigate this and
106 to dissociate task-related activity from activity related to metacognitive experiences.

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Materials and Methods

111 Participants

112 Thirty-one participants, 17 female and 14 male, participated in return for a monetary
113 compensation (£15). Mean age of the sample was 24.3 years ($SD = 5.2$, range 19-42). All participants
114 were right-handed, had normal or corrected-to-normal vision, had no history of epilepsy and were
115 not taking psychoactive drugs. The study was approved by the Ethics Committee of the University of
116 Essex and written informed consent was obtained from each participant prior to the experimental
117 session. Because of intense sweating, caused by extreme hot weather conditions, and resulting noise
118 on the EEG recordings, the data of six participants were unfit for analyses. The data of one additional
119 participant were excluded because of technical problems with the EEG recording.

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121 Experimental procedure

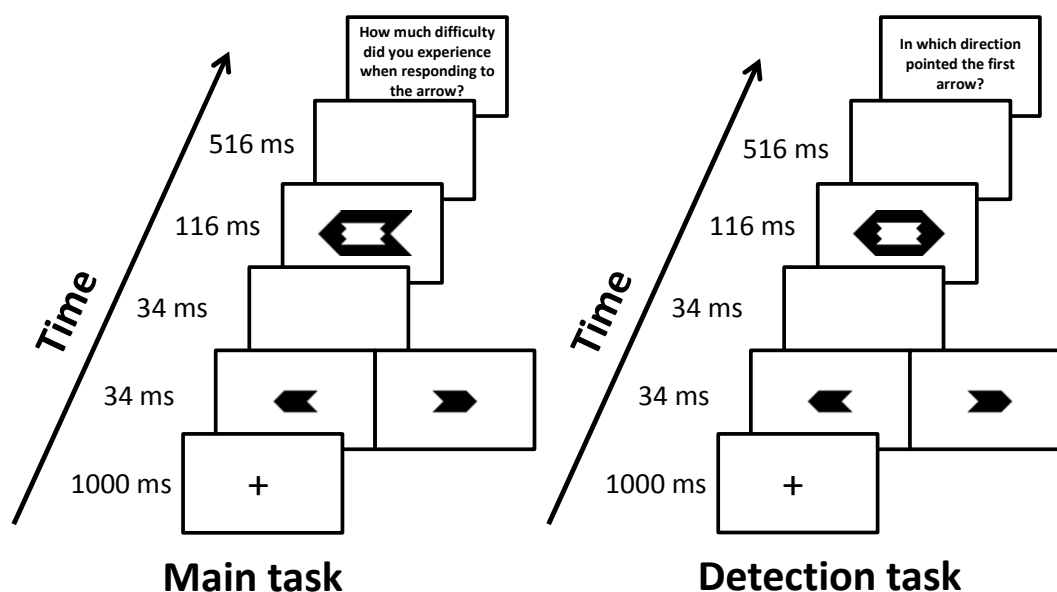
122 Participants were seated in a dimly lit room for the duration of the experimental session.
123 Participants completed a masked priming experiment in which they additionally were asked to report
124 about the metacognitive experience associated with their response (see Figure 1). Each experimental
125 trial started with a fixation cross for 1000 ms. Subsequently, a prime arrow (1.5° wide and 0.7° high)
126 pointing to the left or right was presented for 34 ms followed by a blank screen for 34 ms. Then, a
127 target arrow (3.3° wide and 1.4° high) pointing to the left or right was presented for 116 ms followed
128 by a blank screen. Because the prime arrows fitted perfectly within the contours of the target arrow
129 (i.e., metacontrast masking; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003), primes
130 were rendered invisible. This has the major advantage that task performance and metacognitive
131 experiences are influenced without participants being aware of the visual stimuli driving these
132 changes (Chambon & Haggard, 2012; Desender et al., 2014; Wenke et al., 2010). Participants were
133 asked to respond as fast and accurate as possible to the direction of the target. They were instructed
134 to press “d” in response to a left pointing target arrow and “k” in response to a right pointing target
135 arrow with the middle finger of each hand on a qwerty keyboard. If a response to the target was
136 registered within 3000 ms, a blank screen was presented for 516 ms, followed by a screen asking
137 participants a metacognitive question: “How much difficulty did you experience when responding to
138 the arrow?”. They could answer either by pressing the “o” key with the ring finger of their right hand
139 (“Rather more difficulty”) or by pressing the “m” key with the index finger of their right hand
140 (“Rather less difficulty”). The wordings ‘rather more’ and ‘rather less’ were used in order to stress
141 that the difference between both metacognitive experiences is small, a subtlety that is potentially
142 lost when using the terms ‘easy’ versus ‘difficult’. There was no time limit to answer this question.
143 The inter-trial interval was 800 ms.

144 Each participant started with 20 practice trials in which the metacognitive question was
145 omitted. Subsequently, the experimenter explained that participants had to rate their experience
146 associated with a trial after each response. The experimenter motivated participants to use all
147 information available to them (i.e., difficulty, error-tendency, response fluency) to answer this
148 question. Participants were informed that there would be an equal amount of “more difficult” and
149 “less difficult” trials, and they were motivated to keep a balance between these responses.
150 Participants received 20 additional practice trials with the metacognitive question. After these two
151 training phases, each participant performed eight blocks of 80 trials each. In each block, half of the

152 trials were congruent (i.e., prime and target pointing in the same direction), and half were
 153 incongruent (i.e., prime and target pointing in opposite directions) creating a response conflict.

154 Only after the main experiment, participants were informed about the presence of the
 155 primes, and participated in a subsequent detection task. In this task, participants were instructed to
 156 categorize the direction of the prime arrows, instead of the target arrows. During the detection task,
 157 targets were neutral with heads pointing in both directions to ensure that participants were not
 158 accidentally responding to the target. The detection task comprised of 100 trials.

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 162 *Figure 1.* Example of a trial sequence in the main task (left) and in the detection task (right).
 163 Because primes fitted perfectly into the counters of the target, they were visually imperceptible.

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166 EEG recording and data pre-processing

167 EEG data were recorded from 64 scalp locations (actiCHamp, Brain Products GmbH, Germany)
 168 with a sample rate of 500 Hz. Data were segmented from -500 ms to 2000 ms relative to target onset.
 169 First, segments containing artefacts were identified by visual inspection and removed. Next,
 170 eyeblinks were removed using Independent Component Analysis (ICA), removing 1.47 components
 171 on average (range 1 - 2), and segments containing values $\pm 200 \mu\text{V}$ were excluded using extreme
 172 value rejection. Bad (noisy) channels were replaced by an interpolated weighted average from
 173 surrounding electrodes using the EEGLAB toolbox (Delorme & Makeig, 2004) in Matlab. Finally,
 174 segments containing further artefacts, identified by visual inspection, were removed prior to
 175 averaging. For plotting purposes only, data were filtered using a 20 Hz low pass filter.

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177 Statistical approach

178 In order to perform reliable analyses on our EEG data, a minimum number of 20 trials in each
 179 cell of the 2 by 2 interaction between congruency and metacognition was required. Due to the
 180 nature of our metacognitive measure, the data of nine participants contained less than 20
 181 observations in at least one of these four cells ($M = 6$, range = 0-15). For seven of them, this was

182 caused by very high metacognitive performance (on average 79% correct classifications) leaving too
183 few incorrect metacognitive responses. The other two participants showed a strong response bias,
184 using almost exclusively the 'easy' option. Due to this unequal distribution, these participants were
185 excluded from further analysis, leaving 15 participants in the final sample (five males, $M_{\text{age}} = 24.5$
186 years, $SD = 6.7$, range 19-42). Although the final sample size is sufficiently large to perform reliable
187 analyses, one should keep in mind that this drop in sample size could potentially obscure some
188 effects. To deal with this potential worry, we qualified our main ERP findings by additionally
189 computing the Bayes Factor (BF) associated with each effect, using the default priors in the
190 BayesFactor package (Morey & Rouder, 2014). Compared to classical p -values, a BF has the
191 advantage that it can dissociate between data in favor of the null hypothesis ($BF < 1/3$), data in favor
192 of the alternative hypothesis ($BF > 3$) and data that is not informative ($BF \approx 1$), (by Jeffreys's, 1961,
193 convention). As can be found below, our BF results showed that for all non-significant p -values there
194 was evidence in favor of the null, whereas for all significant p -values there was evidence for the
195 alternative hypothesis. The only exception was the main effect of metacognition in the P3 time
196 window ($p = .08$, $BF = 1.10$), where the BF suggested that the data is not informative. To examine
197 whether metacognitive experiences are related to the N2 and/or the P3, we first examined standard
198 ERPs. To complement this approach, a more data-driven strategy was used in which a classifier was
199 trained to predict the congruency status of individual trials, and subsequently it was tested if this
200 classifier contained information about the metacognitive experience associated with each trial.
201 Above and beyond the standard ERPs, this approach allows us to examine whether congruency
202 information in the N2 and P3 is related to metacognitive experiences. Finally, source localization was
203 used to confirm the relation between the ACC and the N2, and to investigate the neural origin of the
204 P3.

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ERP analyses

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Single-trial analysis

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To complement the standard ERP analysis, we also analyzed the data using a more data-driven approach. Based on the results from the ERP analysis (i.e., the interaction between

226 congruency and metacognition in the P3; see below), we examined whether information about
227 congruency on the single-trial level would predict the associated metacognitive experience. To
228 achieve this, we used single-trial analyses and examined whether a classifier trained on congruency
229 also contains information about metacognition. More specifically, the N2 and P3 components were
230 analyzed on individual trials using the logistic-regression based linear derivation method introduced
231 by Parra et al. (2005). An important advantage of this method is that it does not specify the spatial
232 topography of the effects beforehand. This approach identifies the spatial distribution of scalp EEG
233 activity in a given time window that maximally distinguishes two conditions (e.g., congruent versus
234 incongruent) to deliver a scalar estimate of component amplitude on each trial. The derived
235 estimates have a high signal-to-noise ratio because the discriminating component acts as a spatial
236 filter, estimating component amplitude as a spatially weighted average across electrodes for each
237 trial. The single-trial analysis was conducted separately for each participant by training a logistic
238 regression classifier to discriminate congruency in either the N2 or the P3 time window. In a first step,
239 the reliability of the classification was tested using a 10-fold cross validation approach in which the
240 classifier was trained on 90 % of the trials and tested on the remaining 10 %. This procedure was
241 repeated 10 times, on each occasion keeping a different 10 % of the trials for testing. For each
242 participant, we quantified our ability to successfully classify individual trials by calculating the Az
243 score, which gives the area under the receiver operating characteristic (ROC) curve, derived from
244 signal detection theory (e.g., Stanislaw & Todorov, 1999). To test for the significance of the single-
245 trial classification, the distribution of this Az score was calculated by running 100 permutations of our
246 classifier. This distribution was then compared to 100 permutations of Az scores using randomized
247 condition labels, to provide an estimate of the null classification. A different randomization of the
248 condition labels was carried out at each permutation. Group level analyses were performed by
249 computing an average per subject over the permutations, and contrasting classifications made with
250 true and random labels using a paired *t*-test. In a second step, the classifier was trained to predict
251 congruency using all trials, and the resulting estimates were applied to all trials. Although this
252 approach over-fits the data for congruency, it allows us to examine whether a classifier trained on
253 predicting congruency on individual trials contains information about the metacognitive response.
254

255 **Source Localization**

256 Based on the scalp-recorded electric potential distribution, the standardized low resolution
257 brain electromagnetic tomography (sLORETA) software (<http://www.uzh.ch/keyinst/loreta.htm>) was
258 used to compute the cortical three-dimensional distribution of current density (Fuchs, Kastner,
259 Wagner, Hawes, & Ebersole, 2002; Pascual-Marqui, Esslen, Kochi, & Lehmann, 2002). This method is
260 based on the neurophysiological assumption of coherent co-activation of neighboring cortical areas,
261 and computes the smoothest of all possible activity distributions (i.e., no a priori assumption is made
262 on the number and locations of the sources). Note that, although there is a specific prediction that
263 the N2 originates from the anterior cingulate cortex (Jiang, Zhang, & van Gaal, 2015; Van Veen &
264 Carter, 2002), results from these analyses should be treated with caution given the limited spatial
265 precision of EEG. This is especially the case for the P3, for which the *a priori* prediction is unclear. We
266 conducted this method once on a difference wave of the N2 time window measuring congruency (i.e.,
267 Incongruent - Congruent), and once on a difference wave in the P3 time window measuring the
268 interaction in the P3 ($\text{Easy}_{(\text{Incongruent-Congruent})} - \text{Difficult}_{(\text{Incongruent-Congruent})}$). To analyze these difference
269 waves, we used a paired-groups analysis, and tested the N2 and P3 time windows in the

270 corresponding difference waves, using t -statistics with the variance smoothing parameter set to zero.
271 Finally, 5000 permutations were performed to compute correct thresholds for t values in order to
272 test for significance at an alpha level of .05. These computations are performed in a realistic head
273 model using the MNI152 template, with the three-dimensional solution space restricted to cortical
274 gray matter. The intracerebral volume is partitioned in 6239 voxels at 5 mm spatial resolution.
275

Results

Behavioral results

Metacognitive experience of difficulty

Because performance in responding to the target arrow was at ceiling level (96.7%) and metacognitive responses to incorrect trials are quite trivial, we deleted error trials (3.3%), trials following an error (3.1%) and the first trial of each block (1.2%) from all following analyses. Then, it was examined whether participants' metacognitive *experiences* (i.e., whether a trial was as experienced as easy or difficult), coincided with the actual congruency, which would show evidence of above chance-level metacognitive *performance*. Note that one should be careful not to confuse basic task performance (which was at ceiling level) and this measure of *metacognitive* performance. We used the data of the main experiment to calculate a d' based on signal detection theory (henceforth called conflict- d), which provides a measure of metacognitive performance while controlling for response bias (Green & Swets, 1966). Incongruent trials were treated as signal, and congruent trials were treated as noise. The "difficult" response was considered a hit on incongruent trials and a false alarm on congruent trials. Hit proportions were computed by dividing the total number of hits by the number of signals, and false alarm proportions were computed by dividing the total number of false alarms by the number of trials where no signal was present. Mean conflict- d was 0.54, showing significant above chance level metacognitive performance, $t(14) = 3.01, p = .009$. Participants correctly classified congruent trials as easy and incongruent trials as difficult in 59% of the trials. Trials judged to be easy were more frequently congruent (36.9%) than incongruent (26.9%), whereas trials judged to be difficult were more frequently incongruent (22.4%) than congruent (13.8%). Next, to test if metacognitive accuracy is based on participants' capacity to introspect on their own RTs (Marti, Sackur, Sigman, & Dehaene, 2010), a subset of the data was selected in which RTs for congruent and incongruent trials were matched. For each congruent trial, an incongruent trial was randomly selected whose RT deviated 5 ms maximally. Trials that could not be matched across conditions were discarded. In this RT-matched set, metacognitive performance was still reliably above chance level, conflict- $d = .45, t(14) = 2.56, p = .023$, with participants classifying 57% of the trials correctly. This finding shows that participants were able to introspect on the presence of response conflict, even in the absence of differences in response time¹.

To confirm that this above chance-level categorization is not caused by prime perception, prime visibility was assessed using the data of the detection task. A d' measure (treating left pointing primes as signal) was calculated and this measure did not deviate from chance level (i.e., zero), $d' = -0.019, t(14) = -0.25, p = .81$, indicating that participants were completely unable to dissociate left from right pointing primes. Furthermore, no correlation was found between conflict- d and prime visibility, $\beta_1 = -0.361, t(14) = -0.57, p = .57$, showing that participants' metacognitive capacity was independent from prime visibility. A positive significant intercept, $\beta_0 = .53, t(14) = 2.89, p = .013$, was observed, demonstrating that even when prime visibility was statistically zero, we still observed above chance level metacognitive performance (Greenwald, Klinger, & Schuh, 1995).

¹ When analyzing the complete sample ($N = 31$), these behavioral results were similar. Metacognitive performance was above chance level (64% correct), conflict- $d = .92, t(30) = 4.79, p < .001$. This was also the case when congruent and incongruent trials were matched for response time (61% correct, conflict- $d = .79, t(30) = 4.40, p < .001$). Finally, RTs still showed both the main effect of congruency, $F(1,30) = 56.84, p < .001$ and of metacognitive response, $F(1,30) = 27.01, p < .001$.

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315 Target responses

316 To analyze the responses to the target arrow, median RTs were submitted to a 2 (congruency:
317 congruent or incongruent) x 2 (metacognitive response: easy or difficult) repeated measures ANOVA.
318 A main effect of congruency was observed, $F(1,14) = 18.46$, $p < .001$: RTs were faster on congruent
319 (445 ms) than incongruent trials (486 ms). There was also a significant main effect of metacognitive
320 response, $F(1,14) = 12.28$, $p = .004$, indicating that trials labeled as difficult were responded to slower
321 (521 ms) than trials labeled as easy (465 ms). The interaction between both factors was not
322 significant, $F < 1^2$.

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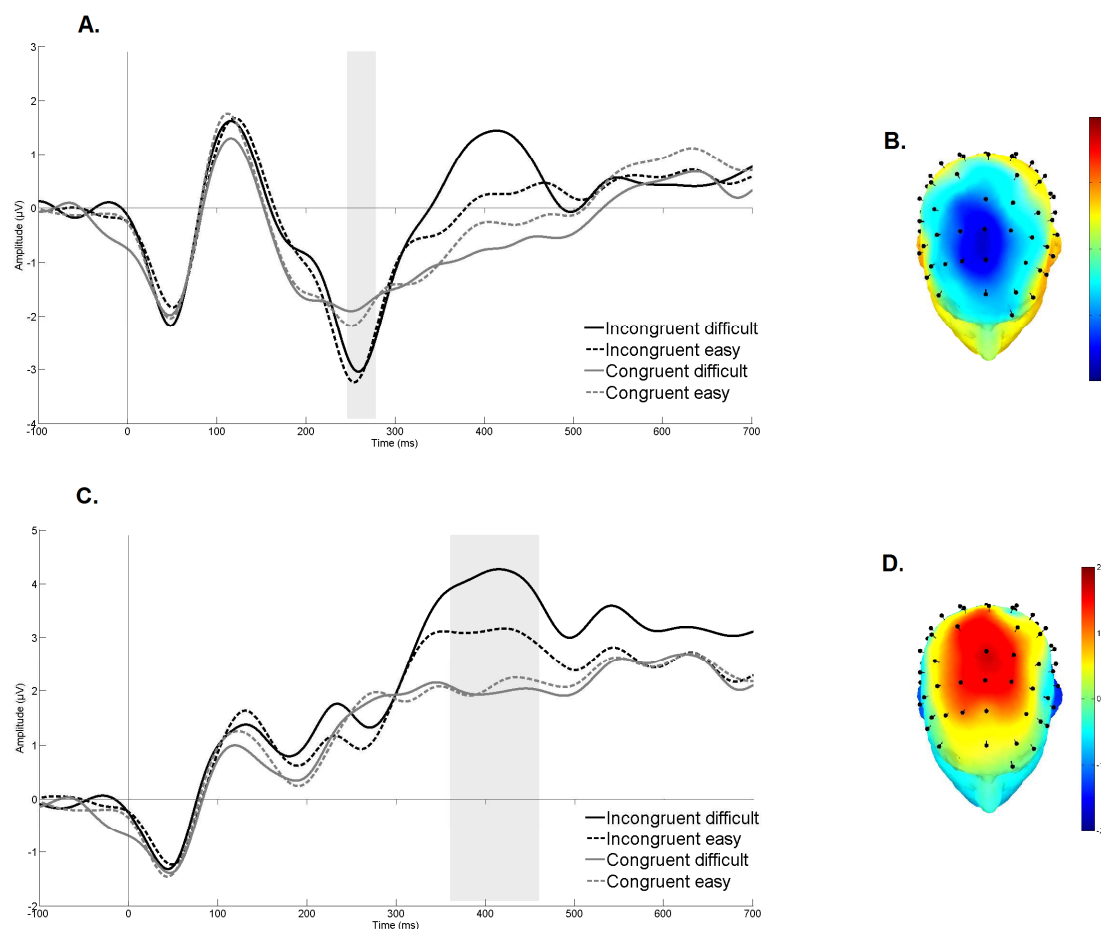
324 Electrophysiological results**325 Stimulus Locked ERPs**

326 Figures 2A and 2C present the grand average stimulus-locked ERPs for fronto-central and
327 centro-parietal electrodes, respectively, dependent on congruency and metacognitive experience.
328 We observed an N2 in a time window between 246 ms and 278 ms post-stimulus, located at fronto-
329 central electrodes (FCz, Fz; see Figure 2B), followed by a P3 in a time window between 360 ms and
330 460 ms post-stimulus, located around central electrodes (CPz, Cz, FCz; see Figure 2D).

331 A repeated measures ANOVA with the factors congruency (congruent or incongruent) and
332 metacognitive experience (easy or difficult) on the mean average voltage during the N2 time window
333 across electrodes FCz and Fz indeed showed a main effect of congruency, $F(1,14) = 10.47$, $p = .005$, BF
334 $= 8.52$. The amplitude of incongruent trials was more negative than that of congruent trials. Crucially,
335 there was no main effect of metacognition, $F < 1$, $BF = 0.29$, nor an interaction between both factors,
336 $F < 1$, $BF = 0.28$. A post-hoc t -test showed that even the small difference between incongruent trials
337 judged to be easy and incongruent trials judged to be difficult that can be seen in Figure 2A was far
338 from significant, $p > .80$, $BF = 0.27$. Exactly the same results were found when the procedure
339 described above to control for differences in RTs was applied.

340

² This same analysis on the error rates yielded no significant effect of congruency, $F(1,14) = 3.11$, $p = .10$, a trivial main effect of metacognition, $F(1,14) = 12.56$, $p = .003$, and no interaction, $p > .27$.



341
 342 *Figure 2.* A. Grand average of stimulus locked ERPs for fronto-central electrodes (FCz, Fz). The
 343 gray bar reflects the N2 time window (246ms to 278ms). B. Voltage plot for the N2 congruency effect.
 344 C. Grand average of stimulus locked ERPs for centro-parietal electrodes (CPz, Cz, FCz). The gray bar
 345 reflects the P3 time window (360ms to 460ms). D. Voltage plot for the P3 congruency effect.
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347 The same repeated measure ANOVA on the P3 time window on the average of the CPz, Cz
 348 and FCz similarly showed a main effect of congruency, $F(1,14) = 35.25$, $p < .001$, $BF = 702.17$. The
 349 amplitude of incongruent trials was more positive than that of congruent trials. The main effect of
 350 metacognition was close to significance, $F(1,14) = 3.63$, $p = .08$, $BF = 1.10$. Crucially, there was a
 351 significant interaction between both factors, $F(1,14) = 8.01$, $p = .013$, $BF = 4.40$, showing that the
 352 effect of metacognition on the P3 was limited to incongruent trials. Post-hoc t -tests showed that
 353 incongruent trials judged to be difficult and incongruent trials judged to be easy differed both from
 354 each other and from all other trial types (all p 's $< .018$, all BF 's > 3.42). Only the difference between
 355 easy and difficult congruent trials was not significant ($p = .65$, $BF = 0.29$). Again, the same pattern of
 356 results was observed in an RT-matched subset of the data, indicating that our results reflect

357 metacognitive experiences associated with response fluency, and not just a mere read-out of
 358 reaction times³.

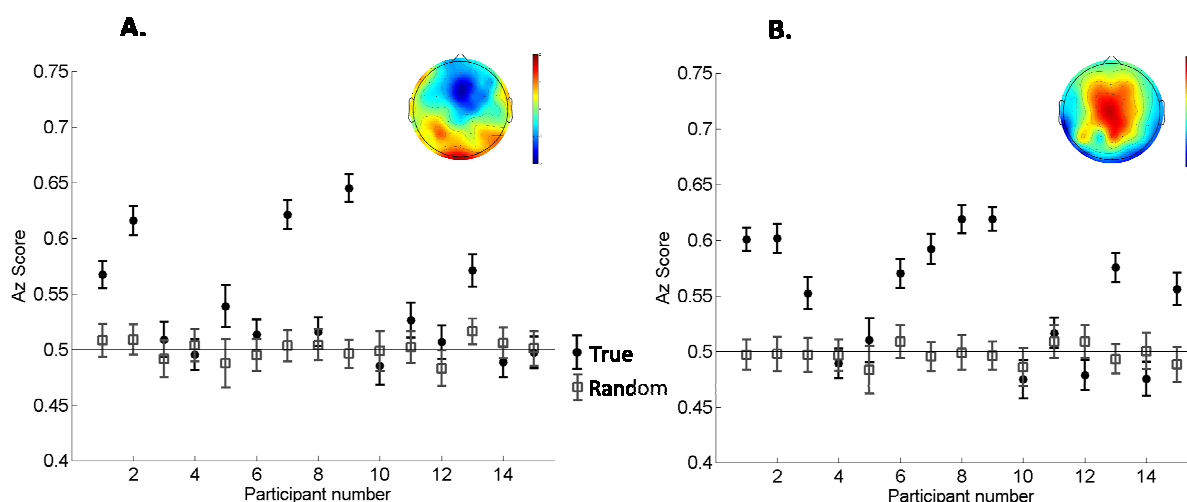
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360 Single-trial analysis

361 First, to get an indication of the robustness of our classifier, we examined the classification
 362 (Az) scores for each participant when predicting congruency based on the N2 (Figure 3A) and the P3
 363 (Figure 3B) time-window. On the individual level, we were able to classify significantly better
 364 compared to random classification for 8 of 15 participants when predicting the N2, and for 9 of 15
 365 participants when predicting the P3. On a group level, both predictions for the N2, $t(14) = 3.08$, p
 366 $= .008$, and the P3, $t(14) = 3.25$, $p = .005$, were significantly better than random classification. As can
 367 be seen in Figure 3, this data-driven approach gives a topography that is highly consistent with the
 368 ERP analysis. Hence, this single-trial analysis provides us with reliable classification performance.

369 Next, it was examined whether a classifier trained on all data to predict congruency on
 370 individual trials contains information about the metacognitive response. As such, we extracted
 371 congruency probabilities associated with each trial from the classifier, and submitted these to a
 372 repeated measures ANOVA, with the factors congruency and metacognitive response as within-
 373 subject factors. For the P3 time window, this analysis showed the trivial main effect of congruency,
 374 $F(1,14) = 329.06$, $p < .001$, and importantly, an interaction with metacognitive response, $F(1,14) =$
 375 5.64 , $p = .032$. For incongruent trials, the probability scores significantly differentiated between easy
 376 and difficult trials, $t(14) = 3.25$, $p = .005$, whereas this was not the case for congruent trials, $p > .60$.
 377 For the N2 time window, this analysis showed only the trivial main effect of congruency, $F(1,14) =$
 378 236.87 , $p < .001$, but no interaction with metacognitive report, $p > .19$. Hence, congruency
 379 information on the individual trial level in the N2 time window does not contain information with
 380 regard to the metacognitive response (see Figure 4).

381

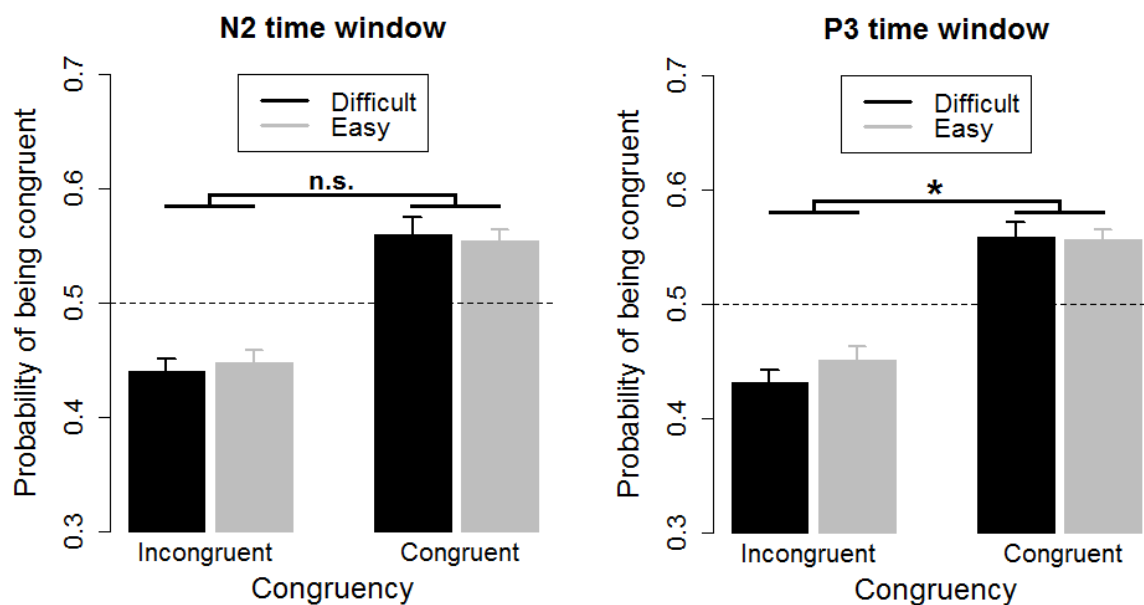


382

383 *Figure 3.* Results of the single-trial analysis. The black dots represent Az scores for individual
 384 participants when predicting congruency based on the N2 time window (A) or the P3 time window

³ Note that our results can also not be explained by a difference in signal-to-noise ratio between the four conditions. When randomly selecting trials from each condition until the number of observations was matched, (separately for each participant), exactly the same pattern of results was obtained.

385 (B). The empty grey boxes show the results of the classifier trained on the same data with
 386 randomized labels. Topographic plots show the scalp projections obtained from the logistic
 387 regression classifier, averaged over subjects. Error bars reflect 95% confidence intervals.
 388



389
 390 *Figure 4.* Congruency probabilities, separated by metacognitive response. Error bars reflect
 391 95% confidence intervals.

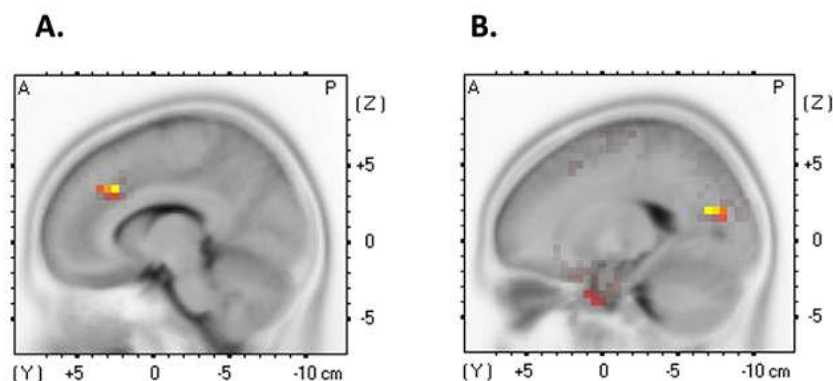
392
 393

394 **Source localization**

395 Our ERP results make a strong case for the P3, but not the N2, being significantly modulated
 396 by metacognitive experience. Next, we examined whether we could link particular brain areas to
 397 these components. First, we examined the neural generator of the congruency effect in the N2.
 398 Given numerous previous reports that this component reflects a sensitivity of the anterior cingulate
 399 cortex (ACC) to competing response demands (Carter & van Veen, 2007), we first wanted to replicate
 400 this finding. In Figure 5A, it can be seen that this prediction is confirmed by the data. A cluster of
 401 voxels in the ACC is more responsive to incongruent compared to congruent trials. Note, however,
 402 that only the maximum peak of activation in this contrast was significant at the .05 level
 403 (MNI coordinates (x, y, z): 10, 25, 35).

404 Second, we examined the neural correlates of the metacognitive experiences on the P3
 405 component. Because our ERP analysis showed that the effect of metacognition was restricted to
 406 incongruent trials, we computed a single difference waveform representing this interaction
 407 ($\text{Difficult}_{(\text{Incongruent-Congruent})} - \text{Easy}_{(\text{Incongruent-Congruent})}$). In Figure 5B, it can be seen that the peak activation
 408 of this contrast is in the left precuneus (MNI coordinates (x, y, z): -20, -70, 20). Apart from this peak,
 409 several other voxels also reached significance at the .05 level (see Table 1). Note that the extent of
 410 these significant areas was quite small, calling for extra caution when interpreting these results.
 411 Therefore, we only tentatively conclude that the interaction between congruency and metacognitive
 412 experience is correlated with activity in the (left) precuneus.

413



414

415 *Figure 5.* Source localization results. A. The congruency effect in the N2 component showed a

416 peak maximum in the ACC. B. The interaction between congruency and metacognition in the P3

417 component showed a peak maximum in the left precuneus.

418

419 **Table 1.** Voxels showing a significant activation at the .05 level ($t > 4.078$) for the interaction

420 between congruency and metacognition in the P3.

| MNI Coordinates | | | t value | Anatomical region |
|-----------------|-----|-----|---------|-------------------------|
| X | Y | Z | | |
| -20 | -70 | 20 | 4.93 | Precuneus |
| -20 | -75 | 20 | 4.86 | Precuneus |
| -20 | -80 | 20 | 4.58 | Cuneus |
| 40 | -20 | 45 | 4.40 | Precentral Gyrus |
| -5 | 30 | 60 | 4.37 | Superior Frontal Gyrus |
| -20 | -80 | 15 | 4.36 | Cuneus |
| 40 | -20 | 50 | 4.29 | Precentral Gyrus |
| 5 | 55 | 40 | 4.23 | Medial Frontal Gyrus |
| -20 | 5 | -40 | 4.23 | Uncus |
| 40 | -20 | 65 | 4.21 | Precentral Gyrus |
| 55 | -25 | 35 | 4.20 | Postcentral Gyrus |
| -20 | 10 | -35 | 4.19 | Superior Temporal Gyrus |
| 45 | -20 | 65 | 4.18 | Postcentral Gyrus |

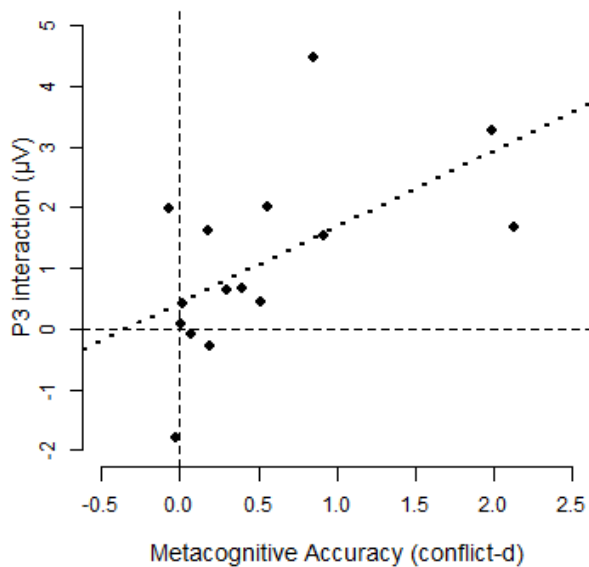
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422

423 ***Link between behavioral and electrophysiological results***

424 Based on our results, we can conclude that the P3 component is crucially linked to
 425 metacognitive experiences. If this is the case, a relation between behavioral performance in the
 426 metacognitive task (as indexed by conflict- d) and the magnitude of the interaction in the P3
 427 component (reflecting that the effect of metacognition was restricted to incongruent trials) should
 428 be expected. A correlational analysis confirmed this, $R^2 = .32$, $\beta = 1.247$, $t(14) = 2.47$, $p = .028$, see
 429 Figure 6: The better participants were able to behaviorally dissociate easy from difficult trials, the
 430 larger the interaction between congruency and metacognition on the P3 component
 431 ($P3_{(\text{congruency} * \text{metacognition})} = \text{Easy}_{(\text{Incongruent-Congruent})} - \text{Difficult}_{(\text{Incongruent-Congruent})}$). Note that the size of the

432 *standard* conflict-P3 component ($P3_{(\text{Incongruent-Congruent})}$) was not predictive of metacognitive
433 performance, $p = .56$.



434

435 *Figure 6.* Relation between metacognitive performance (conflict-*d*) and the size of the
436 modulation between congruency and metacognitive response in the P3 component.

437

Discussion

438
439 The current study is the first report on the temporal dynamics underlying metacognition. In a
440 masked priming paradigm, we induced metacognitive experiences of difficulty by subliminally
441 priming the correct or incorrect response. Because primes were imperceptible, metacognitive
442 experiences do not reflect metacognition about visual perception, but rather introspection on subtle
443 differences in task performance. As expected, participants were able to reliably dissociate easy (i.e.,
444 congruent) from difficult (i.e., incongruent) trials. Our ERPs showed that congruency modulated both
445 the N2 and the P3 component. Crucially, only in the P3, congruency was modulated by the
446 metacognitive experience of difficulty. Complementing this finding, using single-trial analysis, we
447 showed that the magnitude of the P3 modulation by congruency on individual trials was predictive of
448 the metacognitive response. Source localization pointed to the precuneus as the neural generator of
449 metacognitive experiences, although this finding should be treated with caution given the limited
450 spatial precision of EEG. In the remainder, we will discuss the interpretation and significance of our
451 results.

452

The P3 and metacognition

454 Conflict tasks are known to reliably modulate both the N2 and the P3 component (Ullsperger
455 et al., 2014). Interestingly, we did not find any support for a role of the N2 in metacognitive
456 experiences. This suggests that the involvement of the ACC is confined to task-related processes,
457 whereas it is independent of later metacognitive experiences. This finding can aid the interpretation
458 of ACC activation in studies examining the neural correlates of metacognition (e.g., Fleming, Huijgen,
459 & Dolan, 2012). This result also adds to the lively debate on the role of awareness in the detection of
460 response conflicts and response errors, as reflected by the N2 and ERN components, respectively.
461 Some have argued that these components cannot be observed when the presence of response
462 conflict (e.g., Dehaene et al., 2003) or response errors (e.g., Scheffers & Coles, 2000; Shalgi & Deouell,
463 2012) remains below the threshold of awareness, whereas others have challenged this claim (e.g.,
464 Nieuwenhuis et al., 2001; O'Connell et al., 2007). As discussed by Wessel (2012), part of this
465 discrepancy might stem from methodological differences between studies. In particular, studies on
466 error awareness frequently make use of an extra 'awareness-button' that needs to be pressed in the
467 case of an error, which might not be sensitive enough to detect subtle differences in error awareness.
468 In the current work, participants rather rated their metacognitive experience on each trial, which is a
469 more appropriate approach to measure metacognition. Nevertheless, we found evidence that the N2
470 is sensitive to unconscious response conflict, independent of participant's metacognitive awareness
471 (e.g., Jiang et al., 2015).

472 As mentioned in the introduction, the P3 has already been ascribed several different
473 functions, such as stimulus evaluation (Coles et al., 1985; Purmann et al., 2011) or the engagement of
474 attentional resources (Clayson & Larson, 2011; West, 2003). However, because previous studies did
475 not assess metacognitive experiences, they were not able to determine whether the P3 varies as a
476 function of stimulus characteristics, such as response conflict, or as a function of subjective
477 experience (but see Del Cul et al., 2007). Based on the current data, we can conclude that in conflict
478 tasks the P3 component is actually an expression of the interplay between task-related parameters
479 (such as response conflict) and metacognitive experiences. Our analysis indicated that even on
480 individual trials, the size of the modulation of the P3 component by congruency was predictive of
481 whether participants experienced it as an easy or a difficult trial. This was especially the case for

482 incongruent trials, which is reasonable given that only on incongruent trials there is consistent motor
 483 conflict of which participants can become aware. Congruent trials, on the other hand, do not (by
 484 definition) contain motor conflict, and hence congruent trials that are experienced as difficult have to
 485 result from other sources than response conflict. It could for example be that being distracted during
 486 a congruent trial makes you label this trial as “difficult”. While being distracted can lead to difficult
 487 responses on congruent trials, it can never lead to an easy response on incongruent trials, hence it
 488 selectively affects congruent trials. One obvious way to test this distraction hypothesis is to examine
 489 whether RTs to the main target arrow were different on congruent trials that were judged as easy
 490 compared to congruent trials that were judged difficult. We observed that responses were indeed
 491 reliably faster on congruent trials judged as easy (444 ms versus 503 ms), $t(14) = 2.79$, $p = .014$,
 492 suggesting that response time serves as a proxy for task difficulty (Kiani, Corthell, & Shadlen, 2014).
 493 This finding is interesting because, as mentioned in the results section, the effect of congruency on
 494 metacognitive experience was also present in a subset of the data that was matched for RTs,
 495 suggesting that congruency and RT are two independent sources affecting metacognitive experiences,
 496 with only the former modulating the P3. Moreover, note that the EEG waveform associated with
 497 congruent trials labeled as easy or difficult were not different from each other at any other moment
 498 in the epoch (see Figure 2C), strengthening our hypothesis that some source of distraction can lead
 499 to “difficult” judgments on congruent trials. As a final piece of evidence in support of this suggestion,
 500 RTs to the metacognitive question were indeed much slower to difficult congruent trials ($M = 528$ ms
 501 post-response) than to easy congruent trials ($M = 422$ ms post-response), $p = .03$, whereas this was
 502 not the case on incongruent trials, $p = .60$. In sum, we conclude that our P3 modulation might only
 503 reflect metacognitive awareness caused by response conflict, but not by other sources such as
 504 distractions.

505

506 ***The neural correlate of metacognition***

507 Interestingly, source localization pointed to the precuneus as the neural generator of the
 508 modulation by metacognition in the P3. Although source localization results of EEG with 64
 509 electrodes should be treated very cautiously, it is nevertheless interesting to note that this finding
 510 fits well within current literature on metacognition. Although initial functional MRI studies pointed to
 511 the anterior PFC as neural correlate of *visual* metacognition (Fleming et al., 2010; Yokoyama et al.,
 512 2010), recent studies have found the precuneus to be related to metacognition in the memory
 513 domain (Baird, Smallwood, Gorgolewski, & Margulies, 2013; McCurdy et al., 2013). Rather than
 514 stressing this difference in modality (i.e., visual versus memory), these findings can easily be
 515 integrated with the current results by assuming that the functional role of the precuneus is to focus
 516 attention on the target of metacognition. A crucial aspect in our task was that metacognitive
 517 judgments were about the experience of task difficulty. Thus, in order to accurately detect which
 518 experience they had on each trial, participants needed to orient their attention internally, which has
 519 been linked to activity in the precuneus (Vanhaudenhuyse et al., 2011). The metacognitive
 520 experiences in our task might also be highly related to self-consciousness and self-reflection
 521 (Cavanna & Trimble, 2006; Vogt & Laureys, 2005). In line with this suggestion, a recent study argued
 522 that the precuneus may contain common mechanisms for different types of metacognition (visual
 523 and memory; McCurdy et al., 2013), a proposal which fits well with our suggestion that the P3
 524 component reflects the internal orientation of attention. In order to provide more convincing

525 support for our claim linking metacognitive experiences and the precuneus, future studies should
526 aim to replicate this finding using more precise brain imaging techniques, such as fMRI.

527

528 ***The functional role of the P3***

529 Our data provide a compelling case for a role of the P3 in metacognition, for which we see
530 two potential explanations in terms of its functional role. First, the most straightforward explanation
531 is that the P3 reflects a neural correlate of metacognitive awareness. Support for this comes from
532 several studies claiming that the P3 is a neural correlate of conscious access (Del Cul et al., 2007;
533 Kouider et al., 2013), studies claiming that the Pe (which has been linked to the P3; Ridderinkhof et
534 al., 2009) reflects error awareness (Nieuwenhuis et al., 2001), and a recent study linking the
535 experience of agency to the P3 component (Kühn et al., 2011). This latter observation seems of
536 particular interest, given that our methodological approach bears close resemblance to a line of
537 research on the sense of agency (Chambon & Haggard, 2012; Wenke et al., 2010). Here, the same
538 subliminal priming paradigm is used, but responses are additionally followed by a stimulus, whose
539 color is entirely predicted by prime-target congruency. Participants are found to experience a larger
540 sense of agency over colors that follow congruent trials compared to colors following incongruent
541 trials. Hence, response congruency influences the subjective experience of agency. Given the
542 resemblance between this research line and ours, the involvement of the P3 component in both our
543 study and recent work on the sense of agency (Kühn et al., 2011), might point to a general role of the
544 P3 in metacognitive experiences.

545 Alternatively, it can also be that the modulation of the P3 component by metacognition is
546 actually a precursor of metacognition, providing input for metacognitive experiences. Evidence for
547 this possibility comes from a recent study on error awareness that observed a relation between the
548 magnitude of the Pe and the criterion that participants had set to signal their errors (Steinhauser &
549 Yeung, 2010). They found that a high criterion to signal an error resulted in a larger magnitude of the
550 Pe than a low criterion. From this, the authors concluded that the Pe component reflects an evidence
551 accumulator sensitive to the amount of evidence that an error was committed, rather than the
552 neural underpinning of error awareness itself. This is in line with the interpretation of our source
553 localization results, suggesting that the modulation in the P3 reflects the focusing of attention on
554 internal information that enables metacognition. Note, however, that this comparison should be
555 treated with caution. Error rates in conflict tasks are typically below 15 % and are known to produce
556 large orienting behaviors (Notebaert et al. 2009; Jessup et al. 2010), so simply generalizing the
557 functional role of the Pe to that of the P3 might be too simplistic.

558 Finally, an open question for future research will be to examine which specific processes,
559 apart from congruency between prime and target, determine whether a particular trial will be
560 experienced as either easy or difficult. We examined the possibility that differences in response
561 selection might underlie these metacognitive experiences. Another interesting area for further
562 examination is the role of expectancy in metacognitive experiences of difficulty (e.g., Gratton, Coles,
563 Sirevaag, Eriksen, & Donchin, 1988). For example, expecting a particular response (e.g., left) can lead
564 to an 'easy' experience when this expectation is met, and to a 'difficult' experience when it is not met.
565 Likewise, expecting a target stimulus at a given moment in time can lead to an easy experience when
566 this temporal expectation is met, and to a difficult experience when the stimulus is unexpectedly
567 presented earlier or later in time. Interestingly, it could be argued that the mechanism by which
568 expectations influence metacognitive experiences is identical to that examined in the current study.

569 Expecting a particular response to occur, can lead to pre-activation of this response. When this
570 expectation is not met, there will be a response conflict between the expected response and the
571 correct response. This competition between incompatible responses will influence both the
572 performance (i.e., better performance on expected responses) and the metacognitive experience
573 (i.e., 'easy' experience on a predicted response). This very same mechanism can explain the results of
574 the current study. In our study, when an invisible prime triggers the incorrect response, this creates
575 the (unconscious) *expectation* of the incorrect response (Chambon & Haggard, 2012), leading to a
576 response conflict between the primed and the correct response. This competition between two
577 incompatible responses will lead to a reduction in performance and a 'difficult' metacognitive
578 experience. Thus, despite the different origin of the response conflict, the same mechanism of
579 competition between conflicting responses might underlie the modulation of performance and
580 metacognition, both when the conflict is induced by the expectation of a particular response, or
581 when this is induced by means of a priming procedure. Future studies could aim to consistently
582 manipulate expectancy, in order to examine whether the P3 can also be linked to metacognition
583 when using a different manipulation to influence metacognitive experiences.

584

585

Conclusion

586 In the current study, we used EEG to dissociate task-related activity from later metacognitive
587 processes. We observed that both the N2 and P3 component were modulated by congruency, but
588 only in the P3 we observed an interaction with metacognition. We conclude that the N2 component
589 reflects only task-related activation, whereas the P3 component reflects an interplay between task-
590 related activation and metacognitive experiences.

591

592

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