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Running head: Timing of error awareness

Early correlates of error-related brain activity predict subjective timing of error awareness

Francesco Di Gregorio^{1,2}, Martin E. Maier² & Marco Steinhauser²

¹ UO Medicina Riabilitativa e Neuroriabilitazione, Azienda Unità Sanitaria Locale, 40133,
Bologna, Italy

² Department of Psychology, Catholic University of Eichstätt-Ingolstadt, 85072, Eichstätt
Germany

Correspondence should be addressed to:

Francesco Di Gregorio

UO Medicina Riabilitativa e Neuroriabilitazione, Azienda Unità Sanitaria Locale,
Ospedale Maggiore Carlo Alberto Pizzardi, Largo Nigrisoli, 2,
40133 Bologna, Italy

E-Mail: francesco.digregorio@ausl.bologna.it

Abstract

Humans are remarkably reliable in detecting errors in their behavior. Whereas error awareness has been assumed to emerge not until 200 - 400 ms after an error, so-called early error sensations refer to the subjective feeling of having detected an error even before the erroneous response was executed. Here, we collected EEG to track how early error sensations are reflected in neural correlates of performance monitoring. Participants first had to perform a task, and then had to indicate whether an error has occurred and whether this error was detected before or after response execution. EEG results showed that early error sensations were associated with an earlier peak of the error-related negativity (Ne/ERN), a component of error-related brain activity that occurs briefly after the error response. This demonstrates that early error-related activity influences metacognitive judgments on the time course of error awareness, and thus contributes to error awareness.

Keywords:

Early error sensations, error awareness, error-related negativity, error positivity, metacognition.

Introduction

Fast and accurate error detection is a crucial ability of the performance monitoring system. When performing well-learned choice tasks under time pressure, participants immediately recognize almost all of their errors (Rabbitt, 1968, 2002). In these experiments, participants often report to become aware of their errors even slightly before the erroneous response was actually executed. This phenomenon called early error sensations (Di Gregorio et al., 2020) can be observed also in everyday life. For example, when writing an email in a hurry, we sometimes have the feeling that an error is about to occur even before an actual typo is made. Early error sensations stand in stark contrast to the predominant view that error awareness emerges not until 200 to 400 ms after error responses (Nieuwenhuis et al., 2001; Steinhauser & Yeung, 2010), and suggest that error awareness could be influenced by early activity involved in error processing. In the present study, we investigated whether the occurrence of early error sensations is predicted by the strength and timing of early error-related brain activity that emerges at the time of the response. Such a finding would demonstrate that metacognitive judgments have access to early correlates of error monitoring, and thus, that early error-related brain activity contributes to the emergence of error awareness.

Performance monitoring mechanisms in the brain have been extensively investigated using event-related potentials (Gehring et al., 2018; Ullsperger et al., 2014). These studies revealed that errors in human behavior elicit a cascade of brain activity, which starts already at the moment of response execution. The error-related negativity (Ne/ERN; Falkenstein et al., 1991; Gehring et al., 1993) is a fronto-central negativity peaking around 50 ms after errors, and was proposed to reflect the detection of a mismatch (Falkenstein et al., 2000), post-response conflict (Yeung et

26 al., 2004), or prediction error (Holroyd & Coles, 2002). The Ne/ERN is followed by the
27 error positivity (Pe), which is a broad posterior positivity occurring about 200 to 400
28 ms after an error (Falkenstein et al., 1991; Overbeek et al., 2005), possibly reflecting
29 the accumulation of evidence for an error that underlies the emergence of conscious
30 error awareness (Steinhauser & Yeung, 2010; Ullsperger et al., 2014).

31 A common view on error detection is that the Pe is the earliest correlate of error
32 awareness. For instance, when participants are asked to signal whether their
33 response was correct or incorrect, the Pe rather than the Ne/ERN is larger for
34 signaled compared to unsignaled errors (Endrass et al., 2007; Nieuwenhuis et al.,
35 2001). Moreover, the Pe is gradedly modulated by subjective confidence about error
36 commission (Boldt & Yeung, 2015). However, this view has been challenged by
37 studies showing that error-related brain activity earlier than the Pe could reflect the
38 emergence of error awareness. Indeed, a link between Ne/ERN and error awareness
39 has been reported in several studies (Scheffers & Coles, 2000; Wessel et al., 2011),
40 and Ne/ERN latencies have been found to vary with indirect measures of error
41 awareness such as self-corrections (Falkenstein et al., 1997; Fiehler et al., 2005).
42 While these results could imply that also the Ne/ERN contributes to the emergence of
43 error awareness, recent studies argued that the link between Ne/ERN and error
44 awareness is correlative rather than causal (Di Gregorio et al., 2018).

45 A further objection against the idea of the Pe as the earliest correlate of error
46 awareness is the observation of early error sensations. In a recent behavioral study,
47 it was investigated how frequently participants report the feeling of having detected
48 an error already before response execution (Di Gregorio et al., 2020). To this end, a
49 series of experiments was conducted in which different primary tasks (in which errors
50 could occur) and secondary tasks (in which judgments on the primary task responses

51 had to be given) were applied. While a flanker task and a visual discrimination task
52 were used as primary tasks, the secondary tasks required participants either to
53 categorize their responses as correct, early error or late error, or to wager on the
54 occurrence of an early error sensation. Across experiments, participants consistently
55 reported that the majority of errors were associated with early error sensations with a
56 range between 57% and 70% of all errors, and further results demonstrated that
57 these early error sensations were not due to instructions or expectation biases. This
58 demonstrates that early error sensations are a robust phenomenon in choice tasks,
59 which raises the possibility that error awareness could emerge considerably earlier
60 than at the time of the Pe.

61 The present study aimed to reveal early signatures of error awareness by
62 investigating the neural correlates of early error sensations. As in a previous study
63 (Di Gregorio et al., 2020), participants had to classify errors according to whether
64 they already knew that an error was about to occur before the execution of the
65 response (early errors) or not (late errors). We compared error-related brain activity
66 in these early and late errors to reveal which components affect these metacognitive
67 judgments and thus the subjective time course of error awareness. Our analysis
68 particularly focused on the Ne/ERN, a component of error-related brain activity that
69 emerges around the time of the response. We hypothesized that, if the Ne/ERN is
70 related to the emergence of early error sensation and thus error awareness, the
71 Ne/ERN should occur earlier for early errors than for late errors. In addition, we also
72 analyzed the Pe to reveal whether early error sensations are also reflected in this
73 established neural correlate of error awareness. As an earlier onset of the Ne/ERN
74 could imply that evidence accumulation starts earlier while, at the same time, more
75 evidence for an error is provided, we expected that early error sensations are not

76 only associated with a shorter latency of the Pe but also with an increased Pe
77 amplitude.

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Method

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Participants

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32 participants (26 female) between 19 and 31 years of age ($M = 22.8$, $SE =$

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0.65) participated in the experiment. All participants had normal or corrected to

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normal vision, were recruited from the student population at the <<University

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removed for double-blind review>> and received course credit or 8 Euro per hour for

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participation. The study was approved by the ethical committee of the <<University

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removed for double-blind review>> and all participants provided informed consent.

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Apparatus

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A PC running presentation software (Neurobehavioral Systems, Albany, CA)

89

controlled stimulus presentation and response registration. Stimuli were presented on

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a 21-inch color monitor (60 Hz refresh rate) at a viewing distance of 70 cm.

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Stimuli and procedure

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The experiment consisted of a primary flanker task and a secondary task, in

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which participants classified their responses in the flanker task. Stimuli of the primary

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flanker task were strings of five horizontal arrowheads in Arial font, subtending a

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visual angle of 4.1° horizontally and 1.4° vertically. The central arrowhead was

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designated as the target and the lateral arrowheads were designated as the flankers.

97

Participants had to identify the direction of the target. In 50% of trials, flankers had

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the same direction as the target (*congruent condition*; e.g. <<<<<<). In the other 50%

99

of trials, flankers had the opposite direction (*incongruent condition*; e.g. <<>><<). Each

100 trial started with the presentation of a fixation cross for 350 ms. Then, the stimulus
101 array was presented for 200 ms followed by a black screen until a response was
102 given. Participants had to identify the direction of the target by pressing the “K” key
103 for left or the “L” key for right on a standard keyboard with the index or the middle
104 finger of one hand (*primary task response*). After the response, another black screen
105 was presented for 1000 ms. Then, a question mark appeared in the screen center to
106 prompt participants to classify their primary task response. To this end, participants
107 had to execute one of four responses with the index finger, middle finger, ring finger,
108 or little finger of the other hand (*secondary task response*). They indicated whether:
109 a) they thought they had responded correctly (correct response), b) they had
110 committed an error accompanied by early error sensations (early error), c) they had
111 committed an error without early error sensations (late error) or d) they had
112 committed an error, but they do not know when they detected the error (I-don’t-know
113 error). The latter category was included to prevent that categorization is biased by
114 guesses (Di Gregorio et al., 2020). Response mappings were counterbalanced so
115 that half of the participants responded to the primary task with the right hand and to
116 the secondary task with the left hand (primary task responses: “K” and “L”; secondary
117 task responses: “A”, “S”, “D” and “F”) and the other half switched hands (primary task
118 responses: “A” and “S”; secondary task responses: “H”, “J”, “K” and “L”).

119 The experiment consisted of eight test blocks with 64 trials per block. Each
120 block contained 16 instances of each of the four possible stimuli in randomized order.
121 Prior to the test blocks, participants performed two practice blocks (32 trials each)
122 without a secondary response to practice the primary task and two further practice
123 blocks in which the secondary task response was introduced. Before the
124 administration of the two secondary task practice blocks, participants were instructed

125 about early error sensations (Di Gregorio et al., 2020). We told participants that
126 sometimes, the sensation could arise that they are about to commit an error already
127 before the incorrect key was pressed, and that they should indicate whether this was
128 the case or not on error trials. Prior to each of these practice blocks, participants
129 were instructed to respond faster to the primary task whenever the error rate in the
130 preceding block was below 25%.

131 *EEG Data acquisition*

132 The electroencephalogram (EEG) was recorded during the task using a
133 BIOSEMI Active-Two system (BioSemi, Amsterdam, The Netherlands) with 64 Ag-
134 AgCl electrodes from channels Fp1, AF7, AF3, F1, F3, F5, F7, FT7, FC5, FC3, FC1,
135 C1, C3, C5, T7, TP7, CP5, CP3, CP1, P1, P3, P5, P7, P9, PO7, PO3, O1, Iz, Oz,
136 POz, Pz, CPz, Fpz, Fp2, AF8, AF4, AFz, Fz, F2, F4, F6, F8, FT8, FC6, FC4, FC2,
137 FCz, Cz, C2, C4, C6, T8, TP8, CP6, CP4, CP2, P2, P4, P6, P8, P10, PO8, PO4, O2
138 as well as the left and right mastoid. The CMS (Common Mode Sense) and DRL
139 (Driven Right Leg) electrodes were used as reference and ground electrodes.
140 Vertical and horizontal electroculogram (EOG) were recorded from electrodes above
141 and below the right eye and on the outer canthi of both eyes. EEG and EOG data
142 were continuously recorded at a sampling rate of 1024 Hz. All electrodes were offline
143 re-referenced to the linked mastoids, re-sampled to 512 Hz and filtered with a 0.5 -
144 25 Hz band-pass filter.

145 *Data analysis*

146 Trials were classified according to stimulus congruency (congruent and
147 incongruent), primary task response (correct, error) and secondary task response
148 (correct, early error, late error and I don't know error). For all reported analyses,
149 effects of variables with more than two levels were tested by analyses of variance

150 (ANOVAs) with repeated measurement. To compensate for violations of sphericity,
151 Greenhouse–Geisser corrections were applied whenever appropriate (Greenhouse &
152 Geisser, 1959), and corrected p -values but uncorrected degrees of freedom are
153 reported. Differences between conditions were tested by planned comparisons using
154 two-tailed t -tests for dependent samples and Cohen's d (dz) are reported. Moreover,
155 95% confidence intervals for the differences (CI) and scaled-information Bayes
156 Factor (scale value = 0.707; Rouder et al., 2009) for testing the alternative
157 hypotheses against the null hypothesis (BF_{10}) are reported.

158 Response time (RT) in the primary task was defined as the time interval
159 between the onset of the stimulus and the subsequent key press. To control for
160 outliers, trials were excluded whenever the RT of the primary task response was 3
161 standard deviations above or below the condition mean. 1.71% ($SE = 0.4\%$) of all
162 trials were excluded in this way. All frequency data were arcsine-transformed before
163 statistical analyses (Winer, 1971).

164 *ERP Data.*

165 ERP data were analyzed using custom routines in MatLab R2013b
166 (Mathworks, Natic, MA) and EEGLAB v13.0.1. Epochs from 200 ms before and 600
167 ms after the response were extracted from the continuous EEG. Because the
168 Ne/ERN typically emerges slightly before the response, the average voltage in a time
169 window from 150 ms to 50 ms before the response was used as baseline (Di
170 Gregorio et al., 2016). Epochs contaminated with artifacts were identified using two
171 methods from the EEGLAB toolbox (Delorme et al., 2007). An epoch was excluded
172 (1) whenever the voltage exceeded 300 μV in order to remove epochs with large
173 peaks, and (2) whenever an epoch deviated more than five standard deviations from
174 the mean of the joint probability distribution to remove trials with improbable data

175 (pop_eegthresh and pop_jointprob functions, respectively, in EEGLAB). The mean
176 percentage of trials excluded in this way was 8.79% ($SE = 1.45\%$). After artifact
177 rejection, the average number of congruent error trials was 7.7 ($SE = 1.4$). Therefore,
178 congruent trials in all conditions were excluded from EEG analyses because these
179 trial numbers do not meet the requirements for reliable measurement of error-related
180 brain activity (Olvet & Hajcak, 2009). For the incongruent trials, the condition with the
181 smallest number of trials ('I-don't-know' error) had an average of 8 trials ($SE = 1.8$),
182 but 19 participants had less than 6 trials in this condition. Thus, also incongruent 'I-
183 don't-know' errors were excluded from the EEG analyses. The remaining error
184 conditions considered for the EEG analyses had an average trial number of 46.6 (SE
185 $= 6.7$) for incongruent early errors and of 30.5 ($SE = 6.5$) for incongruent late errors.
186 Nevertheless, 5 participants with less than 6 error trials in one of the remaining
187 conditions were excluded from the ERP analyses (Olvet & Hajcak, 2009). An
188 independent component analysis (ICA) (Bell & Sejnowski, 1989) was performed to
189 correct EOG artifacts. This was done using a multistep correlational template-
190 matching process as implemented in CORRMAP v1.02 (Campos Viola et al., 2009).
191 Topographies of ICs labeled as artifacts by the CORRMAP procedure were visually
192 inspected and then removed from the data using inverse matrix multiplication.
193 Epochs were then averaged separately for each participant and for the considered
194 conditions.

195 We used two methods to quantify Ne/ERN and Pe amplitudes, which both rely
196 on the error minus correct difference wave. First, the maximum difference was
197 employed because it also allows to quantify both, the amplitude and the latency of a
198 component, which is particularly important in the present study. Second, the mean
199 difference in a specific time window was calculated because it is the most common

200 measure, although it cannot be used to extract latencies. For the Ne/ERN, both
201 approaches were applied in a time window between 0 ms and 200 ms relative to the
202 response at electrode Fz (Endrass et al., 2007; West & Travers, 2008). For the Pe,
203 we considered a time window between 200 ms and 400 ms relative to the response
204 at electrode Pz (Overbeek et al., 2005). As a result, we obtained three measures for
205 each component: 1) The maximum amplitude difference between correct and error
206 trials, 2) the latency of the maximum amplitude difference, and 3) the mean
207 difference between correct and error trials.

208 In addition, we analyzed stimulus-locked epochs ranging between -200 and
209 500 ms relative to the stimulus applying a baseline between -200 and 0 ms. We
210 restricted this analysis to the P1 and N1 as later stimulus-locked components
211 overlapped with response-locked error-related components. Whereas the P1 was
212 quantified as the positive peak in a time window between 0 and 100 ms, the N1 was
213 quantified as the negative peak between 100 ms and 200 ms (Krigolson & Holroyd,
214 2007). Both components were analyzed at electrode Oz where these components
215 have maximal amplitudes (Barnes et al., 2014). These analyses were meant to
216 reveal whether early and late errors differed with respect to early visual processing
217 and thus with respect to the error source.

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Results

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Behavioral Data.

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In a first step, we analyzed performance in the primary task. The mean error rate in the primary task was smaller for congruent trials ($M = 3.23\%$, $SE = 0.62\%$) compared to incongruent trials ($M = 15.1\%$, $SE = 1.3\%$), $t(31) = 11.93$, $p < .001$, $d_z =$

224 2.2, 95% CI = [10.1, 14.2], $BF_{10} = 48215$. Furthermore, a congruency effect with
225 faster RTs for congruent correct trials ($M = 376$ ms, $SE = 11$ ms) than incongruent
226 correct trials was revealed ($M = 478$ ms, $SE = 19$ ms), $t(31) = 10.1$, $p < .001$, $d_z =$
227 1.8, 95% CI = [80.8, 121], $BF_{10} = 18850$.

228

229

Please insert table 1 here

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231 In a second step, we considered the frequencies of secondary task responses
232 for each primary task response and stimulus condition (see Table 1). As observed in
233 previous studies (e.g., Steinhauser et al., 2008), error detection (independently of
234 error type) was very reliable. 92.5% ($SE = 2.9\%$) of objective errors were categorized
235 as either early error, late error, or I-don't-know error, and this rate was comparable
236 for congruent stimuli ($M = 93.2\%$, $SE = 3.1\%$) and incongruent stimuli ($M = 91.9\%$,
237 $SE = 2.6\%$), $t(31) = 0.79$, $p = .435$, $d_z = 0.14$, 95% CI = [-2.01, 4.55], $BF_{10} = 3.05$.
238 Only 1.8% ($SE = 0.41\%$) of correct responses were categorized as errors. This false
239 alarm rate was higher for the incongruent ($M = 2.71\%$, $SE = 0.56\%$) than for the
240 congruent condition ($M = 0.89\%$, $SE = 0.26\%$), $t(31) = 3.69$, $p = .001$, $d_z = 0.66$, 95%
241 CI = [1.01, 3.11], $BF_{10} = 54.65$.

242

243 A considerable number of errors was categorized as early errors, that is,
244 errors accompanied by early error sensations. Figure 1 shows the relative
245 frequencies of objective errors categorized as early, late and I-don't-know errors
246 among all detected errors. Importantly, the proportion of I-don't-know errors was
247 15.3% ($SE = 4.3\%$), and was comparable for congruent and incongruent stimuli, $t(31)$
248 = 0.23, $p = .818$, $d_z = 0.04$, 95% CI = [-3.73 4.68], $BF_{10} = 2.98$. The frequencies of
early and late errors were subjected to an ANOVA with the variables congruency

249 (congruent, incongruent) and error type (early errors, late errors). The ANOVA
250 showed a significant main effect of error type, $F(1,31) = 14.1$, $p = .001$, $\eta_p^2 = .31$,
251 indicating that early errors ($M = 57\%$; $SE = 5.4\%$) were more frequent than late errors
252 ($M = 27.7\%$; $SE = 4.5\%$). No significant main effect of congruency, $F(1,31) = 0.54$, p
253 $= .818$, $\eta_p^2 = .01$ was obtained, but the interaction between error type and
254 congruency was marginally significant, $F(1, 31) = 3.69$, $p = .064$ $\eta_p^2 = .11$, suggesting
255 that the difference between early and late errors tended to be larger for congruent
256 than for incongruent trials (Fig. 1A).

257 Furthermore, we compared RTs for correct responses, early and late errors (Fig. 1B).
258 Only incongruent trials were considered for this analysis because 20 participants had
259 no error trial in at least one error type condition of the congruent trials. Moreover, in
260 the considered incongruent conditions, 6 participants with less than 5 trials in one
261 condition were excluded. The results of a one-way ANOVA contrasting the three trial
262 types showed a significant effect, $F(2, 75) = 14.72$, $p < .001$, $\eta_p^2 = 0.73$, with larger
263 RTs for the corrects than for the two error types, *all ts* > 10.1 , *all ps* $< .001$, *all dzs* $>$
264 1.8 *all BF*₁₀ > 18850 . Crucially, however, RTs did not significantly differ between
265 early ($M = 354$ ms; $SE = 12$ ms) and late ($M = 359$ ms; $SE = 15$ ms) errors, $t(25) =$
266 0.61 , $p = .551$, $dz = 0.12$, $95\% CI = [-25.7, 14.06]$, $BF_{10} = 3.29$ (Fig 1B). Finally, we
267 compared error signaling RTs for correct responses correctly signaled, early and late
268 errors. The results of a one-way ANOVA contrasting the three trial types in the
269 congruent condition showed a significant effect, $F(2, 52) = 10.18$, $p = .001$, $\eta_p^2 =$
270 $.281$, with slower RTs for detected errors (mean early and Late errors = 637 ms; $SE =$
271 88.94 ms) compared to correct responses ($M = 244$ ms; $SE = 21.12$ ms), *all ts* $>$
272 3.73 , *all ps* $< .001$, *all dzs* $> .718$, *all BF*₁₀ > 52.44 . Moreover, analyses show a
273 tendency towards faster RTs for early ($M = 514$ ms; $SE = 67.61$) compared to late (M

274 = 760 ms; SE = 140 ms) errors, $t(26) = 1.95$, $p = .062$, $dz = .375$, 95% CI = [-13.66,
 275 505], $BF_{10} = 1.44$. However, these results should be treated with caution as
 276 participants were not instructed to signal their errors as fast as possible.

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278

Please insert Figure 1 here

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ERP Data.

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Ne/ERN. Waveforms from electrode Fz (Fig. 2A) revealed more negative amplitudes on error trials compared to correct trials shortly after the response. Scalp topographies reflecting the maximum amplitude difference between correct and error trials show a typical fronto-central distribution in both error types. These Ne/ERNs were reliable and significant for early errors (maximum error minus correct difference amplitude: $-5.85 \mu\text{V}$, SE = $0.76 \mu\text{V}$), $t(26) = 7.78$, $p < .001$, $dz = 1.49$, 95% CI = [-7.41, -4.31], $BF_{10} = 39416$, as well as for late errors ($-7.78 \mu\text{V}$, SE = $1.26 \mu\text{V}$), $t(26) = 6.25$, $p < .001$, $dz = 1.2$, 95% CI = [-10.33, -5.22], $BF_{10} = 16558$. However, a comparison between the two error types revealed no significant difference for the amplitudes, neither for the maximum difference amplitude, $t(26) = 1.76$, $p = .096$, $dz = 0.33$, 95% CI = [-0.36, 4.21], $BF_{10} = 0.93$, nor for the mean difference amplitude (early errors = $-3.60 \mu\text{V}$, SE = $0.79 \mu\text{V}$; late errors = $-4.227 \mu\text{V}$, SE = $0.62 \mu\text{V}$), $t(26) = 0.836$, $p = .411$, $dz = 0.16$, 95% CI = [-0.92, 2.18], $BF_{10} = 2.73^1$. Crucial, however,

¹ As the wide time window of 0 to 200 ms could blunt the effect around 20 to 100 ms when using a mean difference measure, we additionally analyzed mean amplitudes for correct, early and late errors in a time window of 20 to 100 ms after the response. A one-way ANOVA on the variable response type (correct, early and late errors) showed a significant response type effect, $F(2,52) = 20.23$, $p < .001$, $\eta^2 = .438$ with reliable Ne/ERNs for both error types (early errors = $-0.70 \mu\text{V}$, SE = $0.77 \mu\text{V}$, $t(26) = 5.756$, $p < .001$, $dz = 1.11$, 95% CI = [-4.54, -2.15], $BF_{10} = 5456$; late errors = $-1.59 \mu\text{V}$, SE = $0.56 \mu\text{V}$, $t(26) = 5.33$, $p < .001$, $dz = 1.02$, 95% CI = [-5.87, -2.60], $BF = 2102$) compared to correct responses ($2.65 \mu\text{V}$, SE = $0.72 \mu\text{V}$). As with the maximum difference measure, no significant

294 was the question whether the Ne/ERN for both error types differed in their latency.
295 This becomes obvious from Figure 2A (right side) in which the difference waveforms
296 (error minus correct) for early and late errors are compared. The Ne/ERN maximum
297 difference for late errors (78 ms, SE = 9 ms) occurs about 23 ms later than the
298 maximum difference for early errors (55 ms, SE = 5 ms), an observation that is
299 corroborated by statistical testing, $t(26) = 2.85$, $p = .008$, $dz = 0.55$, 95% CI = [6.64,
300 40.69], $BF = 7.73^2$. Additionally, we compared peak latencies in the raw signal of the
301 different response types (correct, early and late errors) in a one-way ANOVA.
302 Although peak latency in the raw signal was shorter for early errors (43 ms, SE = 4
303 ms) than for late errors (52 ms, SE = 8 ms) and correct responses (corrects = 57 ms;
304 SE = 9 ms), the ANOVA did not reveal a significant effect of response type, $F(2,52) =$
305 1.172 , $p = .318$, $\eta_p^2 = .043$. This shows that the latency effect of early errors is
306 reliable only for the difference waveforms. Although raw signal and difference
307 waveforms are both valid methods to quantify Ne/ERN amplitude and latency, the
308 two measures can differ. In particular, while raw measures identify the absolute
309 psychophysiological response after an error, a difference waveform between correct
310 and error trials takes into consideration responses after correct trials and outputs a
311 deviation when a change in the ongoing response is detected (Holroyd & Coles,
312 2002). In other words, difference waveforms can evidence the dissimilarity between
313 error processing and correct response processing and thus indicate the magnitude of

difference was found between the early and late errors, $t(26) = 1.244$, $p = .224$, $dz = .238$, 95% CI = [-0.58, 2.36], $BF = 1.88$.

² Results were confirmed also after application of current source density (CSD) transformation (as applied in previous studies; Kelly & O'Connell, 2013). Importantly, the maximum difference in the error minus correct waveform occurred significantly later for late errors (100 ms, SE = 8 ms) than for early (73 ms, SE = 8 ms), $t(26) = 2.856$, $p = .008$, $dz = .548$, 95% CI = [7.73, 47.45], $BF_{10} = 4.228$.

314 error detection.

315 To provide a better illustration of the time course of the Ne/ERN, we also
316 included the stimulus-locked waveforms from electrode Fz in Figure 3A. Here, the
317 Ne/ERN can be seen in the error waveforms between about 300 and 500 ms.
318 Because RTs of early and late errors were not significantly different, the shift in time
319 between the two waveforms in this time period can be interpreted as the differential
320 evolution of the Ne/ERN for early and late errors.

321 *Pe*. In addition, we also compared early and late errors with respect to the *Pe*,
322 a component that has more frequently been associated with error awareness.
323 Waveforms from electrode Pz (Fig. 2B) revealed more positive amplitudes on error
324 trials than on correct trials starting at around 200 ms after the response. Scalp
325 topographies representing this difference show a posterior distribution for both error
326 types, which is typical for the *Pe*. The *Pe* was reliable and significant for early errors
327 (error minus correct: 8.62 μ V, SE = 1.11 μ V), $t(26) = 7.76$, $p < .001$, $dz = 1.49$, 95%
328 $CI = [6.33, 10.9]$, $BF_{10} = 37909$ as well as for late errors (7.11 μ V, SE = 1.32 μ V),
329 $t(26) = 5.36$, $p < .001$, $dz = 1.03$, 95% $CI = [4.39, 9.83]$, $BF_{10} = 2251$. Crucially, a
330 comparison between the two error types revealed a significant difference in the *Pe*
331 time window as larger *Pe* amplitudes for early errors were found for the mean
332 difference between correct trials and errors, $t(26) = 2.42$, $p = .023$, $dz = 0.47$, 95% CI
333 $= [0.22, 2.79]$, $BF_{10} = 3.24$. For the maximum difference between correct trials and
334 errors, no significant difference was found neither for the amplitude (early errors: 12.2
335 μ V, SE = 1.05 μ V; late errors: 12.1 μ V, SE = 1.44 μ V), $t(26) = 0.08$, $p = .932$, $dz =$
336 0.18 , 95% $CI = [-1.71, 1.87]$, $BF_{10} = 3.79$ nor for the latencies (early errors: 317 ms,
337 SE = 12 ms; late errors: 301 ms, SE = 13 ms), $t(26) = 1.48$, $p = .151$, $dz = 0.284$,

338 95% $CI = [-6.05, 37.16]$, $BF_{10} = 1.38^3$.

339 Taken together, the analyses of response-locked ERPs revealed typical
340 Ne/ERN and Pe components. Most importantly, the Pe amplitude and the Ne/ERN
341 latency were both modulated by the timing of error awareness. Early errors showed
342 earlier Ne/ERN latencies and larger Pe amplitudes compared to late errors.

343 Please insert Figure 2 here

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345 *P1 and N1*. In addition, we analyzed early stimulus-locked correlates of visual
346 attention to investigate whether early and late error differ with respect to the source
347 of an error (see Fig. 3A). However, no differences in amplitudes or latencies were
348 found for the P1 (early errors P1 amplitude: 2.02 μV , SE = 0.43 μV ; late errors P1
349 amplitude: 1.59 μV , SE = 0.68 μV ; $t(26) = 0.72$, $p = .477$, $dz = 0.09$, 95% $CI = [-$
350 $0.81, 1.66]$, $BF_{10} = 2.95$; early errors P1 latency: 54.3 ms, SE = 8.07 ms; late errors
351 P1 latency: 48.4 ms, SE = 7.62 ms; $t(26) = 0.76$, $p = .451$, $dz = 0.08$, 95% $CI = [-9.88,$
352 $21.59]$, $BF_{10} = 2.88$) or N1 (early errors N1 amplitude: -7.07 μV , SE = 0.97 μV ; late
353 errors N1 amplitude: -7.44 μV , SE = 1.18 μV ; $t(26) = 0.52$, $p = .604$, $dz = 0.12$, 95%
354 $CI = [-1.07, 1.81]$, $BF_{10} = 3.34$; early errors N1 latency: 151 ms, SE = 3.91 ms; late
355 errors N1 latency: 156 ms, SE = 4.74 ms; $t(26) = 0.79$, $p = .431$, $dz = 0.08$), 95% $CI =$
356 $[-14.98, 6.59]$, $BF_{10} = 2.82$.

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358 Please insert Figure 3 here

³ Note that after CSD transformation, no differences were found in the Pe mean difference amplitude between the two error types, $t(26) = 0.845$, $p = .406$, $dz = .163$, 95% $CI = [-0.688, 0.287]$, $BF_{10} = 2.71$

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Discussion

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Early error sensation is the subjective experience of becoming aware of an error even before the erroneous response was actually executed (Di Gregorio et al., 2020). The present data indicate that early error sensations are a frequent and robust phenomenon also in the current study. Replicating a previous work (Di Gregorio et al., 2020), behavioral results showed that participants consistently reported early error sensations on error trials in a similar proportion for congruent and incongruent conditions. Moreover, as in the previous study, no RT difference between early and late errors was obtained. Thus, whether or not participants report an early error sensation did not depend on task-related features like congruency or RT. This is interesting as previous studies speculated that response conflict could influence conscious error detection (Yeung et al., 2004). However, the similar RTs for both error types and the absence of a robust congruency effect here and in a previous study (Di Gregorio et al., 2020) on the frequency of early errors suggests that pre-response conflict (i.e., conflict induced by the congruent or incongruent stimulus) did not differ between early and late errors. This speaks against the idea that pre-response conflict is directly involved in the generation of early error sensations.

Our ERP data revealed several signatures of early error sensations. First of all, larger Pe amplitudes emerged for early errors compared to late errors. This again demonstrates that the Pe is linked to error awareness and metacognition (Boldt & Yeung, 2015; Charles et al., 2013; Yeung & Summerfield, 2012). It has been hypothesized that the Pe reflects the accumulated evidence for having made an error (Steinhauser & Yeung, 2010; Ullsperger et al., 2014), based on input from sensory, cognitive, and autonomous systems (Ullsperger et al., 2010; Wessel et al., 2011).

384 The mechanisms of error awareness are thus comparable to a decision process
385 involving lower-level evidence accumulation (i.e., collecting evidence from sensory,
386 cognitive and autonomous systems) and a higher-level decision (i.e., a metacognitive
387 judgment operating on this evidence) (Dehaene et al., 2014). From this perspective,
388 the larger Pe for early errors could indicate that errors accompanied by early error
389 sensations are associated with more evidence, possibly because the accumulation of
390 evidence for an error started earlier for these errors. The absence of an effect on Pe
391 latency could reflect that the earlier onset of evidence accumulation is counteracted
392 by a longer latency of the accumulation process itself (due to the accumulation of
393 more evidence). However, this interpretation is tentative and contradicts the idea of a
394 bounded evidence accumulation process in which evidence is accumulated until a
395 constant criterion is reached (Desender et al., 2021; Steinhauser & Yeung, 2010).
396 Indeed, the idea of a bounded accumulation process receives support from the
397 observation that no effect on Pe amplitude is obtained when analyzing peak
398 amplitudes (rather than average amplitudes).

399 Crucially, our data demonstrate that also error-related brain activity earlier than
400 the Pe is sensitive to the subjective timing of error detection. The Ne/ERN for early
401 errors shows a robustly shorter latency than the Ne/ERN for late errors, suggesting
402 that early error sensations are accompanied by an earlier peak of the Ne/ERN. Note
403 that the time course of Ne/ERN shows a double peak in the early error waveform
404 (see Fig. 3A). This is relatively common in conflict paradigms like the flanker task
405 (Danielmeier et al., 2009; Kirschner et al., 2020). More importantly, the observation of
406 earlier Ne/ERN peaks for early errors provides support for the idea that already early
407 error-related brain activity at around the time of the response contributes to the
408 emergence of error awareness, or, in other words, that metacognitive content is

409 sensitive to this very early activity. Early and late errors differed only in Ne/ERN
410 latency but not its amplitude. This suggests that errors leading to an early error
411 sensation are not associated with a stronger error signal such as stronger post-
412 response conflict (Yeung et al., 2004) or prediction error (Holroyd & Coles, 2002).
413 Rather, they differ in the time point at which this error signal appears possibly
414 reflecting random variation in the build-up of the error signal (e.g., post-response
415 conflict), suggesting a correspondence between the timing of objective error
416 processing and the timing of subjective error awareness. Such a correspondence in
417 timing was found only for the Ne/ERN but not for the Pe, which further points towards
418 the Ne/ERN as a neural correlate of the temporal characteristics of error awareness.

419 *Early error sensations as a metacognitive illusion?*

420 Whereas our data demonstrate an association between Ne/ERN latency and
421 early error sensations, this does not necessarily imply that error awareness emerges
422 at the time point of the Ne/ERN. Such an explanation would neglect the numerous
423 failures to establish a robust relationship between Ne/ERN amplitude and error
424 awareness (e.g., Nieuwenhuis et al., 2001; Steinhauser & Yeung, 2010). An
425 alternative explanation is that error awareness emerges at the time point of the Pe,
426 whereas an early error sensation is a metacognitive illusion that reflects the
427 backdating of the subjective time point of error detection to temporally align error
428 awareness with the emergence of the objective error signal (Di Gregorio et al., 2020).
429 Such a backward referral process has previously been proposed in the domain of
430 visual awareness as a means to synchronize the subjective time point of visual
431 awareness with the onset of the objective stimulus to create a coherent perception in
432 the stream of consciousness (Libet et al., 1979, 1983). In line with these ideas, error

433 awareness might be subjectively backdated to the time point of the earliest neural
434 evidence for an error, which is the Ne/ERN. This would explain why the occurrence of
435 early error sensations is facilitated by an early occurring Ne/ERN, as demonstrated
436 by the present results.

437 The temporal alignment of actions (i.e., an error response) and their effects (i.e.,
438 the feeling of being incorrect) could serve to evoke a sense of agency, i.e., the
439 feeling of being in control of one's actions and action outcomes (Haggard & Tsakiris,
440 2009). Indeed, judgments on the causality of actions and their sensory effects have
441 been shown to correlate with the perceived temporal contiguity between both
442 (Haering & Kiesel, 2016). From this perspective, the phenomenon of early error
443 sensations could be closely related to the phenomenon of intentional binding
444 (Haggard, Aschersleben, et al., 2002; Haggard, Clark, et al., 2002), which is
445 considered to be an implicit measure of agency. Intentional binding refers to the
446 observation that the interval between an action and a subsequent stimulus is
447 underestimated if the action is perceived to have caused this stimulus. Both
448 intentional binding and early error sensations could reflect a backward referral
449 mechanism that serves to temporally align actions and their consequences. In the
450 case of early error sensations, the temporal course of early error-related brain activity
451 (i.e. Ne/ERN latency) is the crucial information for backdating. Indeed, early error-
452 related brain activity can be considered an internal information influencing conscious
453 error detection (Ullsperger et al. 2014) and metacognitive error evaluation (Yeung &
454 Summerfield, 2012). However, one has to note that while backdating (or
455 recalibration) of stimulus onset has been discussed as one source of intentional
456 binding (Moore & Haggard, 2008), other results favored the idea of a change in time
457 perception (Wenke & Haggard, 2009).

458 *Conclusion*

459 The present study demonstrated that the time course of the Ne/ERN is
460 predictive of whether an error is perceived as being detected before the occurrence
461 of a response, a phenomenon we called early error sensation. This shows that
462 characteristics of the Ne/ERN can influence error awareness, but also that
463 metacognitive content is sensitive to this early error-related brain activity. We
464 interpret this finding as reflecting the subjective backdating of error awareness to the
465 time point of the Ne/ERN, which resembles similar phenomena in perceptual
466 awareness (Libet et al., 1979) and the emergence of agency (Haggard, Clark, et al.,
467 2002).

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Author contribution.

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Author note.

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All authors contributed to the study design and study concept. Testing and data collection were performed by FDG and MEM. FDG performed the data analysis and interpretation under the supervision of MS and MEM. FDG drafted the manuscript, and MS and MEM provided critical revisions. All authors approved the final version of the manuscript for submission.

Authors declare no competing interests.

625 **Table 1: Relative frequencies** (in %) of secondary task responses for each
 626 stimulus condition and primary task response.

		Primary Task			
		Congruent		Incongruent	
		Correct	Error	Correct	Error
Secondary Task	Correct	99.1 (0.3)	6.81 (3.1)	97.3 (0.6)	8.1 (2.6)
	Early Error	0.4 (0.1)	58.6 (4.9)	0.7 (0.2)	52.6 (4.7)
	Late Error	0.2 (0.1)	23.0 (3.8)	0.4 (0.2)	28.2 (4.3)
	Don't know	0.3 (0.1)	11.6 (2.4)	1.6 (0.4)	11.1 (2.6)

627 Notes: Brackets contain standard errors of the mean.

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Figure Captions

630 **Figure 1: Behavioral data. A.** Relative frequencies of errors classified as
 631 early, late and I-don't-know errors, separately for congruent and incongruent
 632 condition. **B.** Response times for correct responses, early errors and late errors in the
 633 incongruent condition. ms = milliseconds. Error bars represent standard errors of the
 634 mean.
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636 **Figure 2: Response-locked ERP data. A** Grand average response-locked
 637 ERP waveforms at Fz and waveforms of the difference between errors and correct
 638 trials. Topographies represent the negative peak in the error minus correct difference
 639 waveforms in each error condition in the Ne/ERN time window (shaded gray bar
 640 between 0-200 ms). Bar graphs represent the differences (errors minus corrects) in
 641 Ne/ERN negative peak amplitude and latency. **B** Grand average response-locked
 642 ERP waveforms at Pz and waveforms of the difference between errors and correct
 643 trials. Topographies represent the mean of the error minus correct difference
 644 waveforms in the Pe time window in each error condition (shaded gray bar between
 645 200-400 ms). Bar graphs represent the difference (errors minus corrects) in the Pe
 646 amplitude. The horizontal black arrow represents the time shift of the maximal
 647 Ne/ERN difference between error types. R = response; CR = correct response; μv =
 648 microvolt; ms = milliseconds. Error bars represent the standard error of the mean.
 649

650 **Figure 3. stimulus-locked ERP data. A.** Grand average stimulus-locked
 651 ERPs waveforms at electrode Fz for Stimulus-locked Ne/ERN analyses (shaded gray
 652 bar between 250-450 ms). and **B** waveforms at electrode Oz for P1 (shaded gray bar

653 between 0-100 ms) and N1 analyses (shaded gray bar between 100-200 ms).
654 Topographies show the peaks of the error minus correct difference waveforms in
655 each component and condition. CR = correct responses; μv = microvolt, ms =
656 milliseconds, S = stimulus.

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