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Running head: Timing of error awareness

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

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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 2 monitoring system. When performing well-learned choice tasks under time pressure, 3 participants immediately recognize almost all of their errors (Rabbitt, 1968, 2002). In 4 these experiments, participants often report to become aware of their errors even 5 slightly before the erroneous response was actually executed. This phenomenon 6 called early error sensations (Di Gregorio et al., 2020) can be observed also in 7 everyday life. For example, when writing an email in a hurry, we sometimes have the 8 feeling that an error is about to occur even before an actual typo is made. Early error 9 sensations stand in stark contrast to the predominant view that error awareness 10 emerges not until 200 to 400 ms after error responses (Nieuwenhuis et al., 2001; 11 Steinhauser & Yeung, 2010), and suggest that error awareness could be influenced 12 by early activity involved in error processing. In the present study, we investigated 13 14 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. 15 Such a finding would demonstrate that metacognitive judgments have access to early 16 correlates of error monitoring, and thus, that early error-related brain activity 17 contributes to the emergence of error awareness. 18

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

al., 2004), or prediction error (Holroyd & Coles, 2002). The Ne/ERN is followed by the
error positivity (Pe), which is a broad posterior positivity occurring about 200 to 400
ms after an error (Falkenstein et al., 1991; Overbeek et al., 2005), possibly reflecting
the accumulation of evidence for an error that underlies the emergence of conscious
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 awareness. For instance, when participants are asked to signal whether their 32 response was correct or incorrect, the Pe rather than the Ne/ERN is larger for 33 signaled compared to unsignaled errors (Endrass et al., 2007; Nieuwenhuis et al., 34 2001). Moreover, the Pe is gradedly modulated by subjective confidence about error 35 commission (Boldt & Yeung, 2015). However, this view has been challenged by 36 studies showing that error-related brain activity earlier than the Pe could reflect the 37 emergence of error awareness. Indeed, a link between Ne/ERN and error awareness 38 has been reported in several studies (Scheffers & Coles, 2000; Wessel et al., 2011), 39 and Ne/ERN latencies have been found to vary with indirect measures of error 40 awareness such as self-corrections (Falkenstein et al., 1997; Fiehler et al., 2005). 41 While these results could imply that also the Ne/ERN contributes to the emergence of 42 error awareness, recent studies argued that the link between Ne/ERN and error 43 awareness is correlative rather than causal (Di Gregorio et al., 2018). 44

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

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

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

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

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Method

80 Participants

32 participants (26 female) between 19 and 31 years of age (M = 22.8, SE = 81 0.65) participated in the experiment. All participants had normal or corrected to 82 normal vision, were recruited from the student population at the <<University 83 removed for double-blind review>> and received course credit or 8 Euro per hour for 84 participation. The study was approved by the ethical committee of the <<University 85 removed for double-blind review>> and all participants provided informed consent. 86 87 Apparatus A PC running presentation software (Neurobehavioral Systems, Albany, CA) 88 controlled stimulus presentation and response registration. Stimuli were presented on 89

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

91 Stimuli and procedure

The experiment consisted of a primary flanker task and a secondary task, in 92 which participants classified their responses in the flanker task. Stimuli of the primary 93 flanker task were strings of five horizontal arrowheads in Arial font, subtending a 94 visual angle of 4.1° horizontally and 1.4° vertically. The central arrowhead was 95 designated as the target and the lateral arrowheads were designated as the flankers. 96 Participants had to identify the direction of the target. In 50% of trials, flankers had 97 the same direction as the target (congruent condition; e.g. <<<<>). In the other 50% 98 of trials, flankers had the opposite direction (*incongruent condition*; e.g. <<><<). Each 99

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

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

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

131 EEG Data acquisition

The electroencephalogram (EEG) was recorded during the task using a 132 BIOSEMI Active-Two system (BioSemi, Amsterdam, The Netherlands) with 64 Ag-133 AqCl electrodes from channels Fp1, AF7, AF3, F1, F3, F5, F7, FT7, FC5, FC3, FC1, 134 C1, C3, C5, T7, TP7, CP5, CP3, CP1, P1, P3, P5, P7, P9, PO7, PO3, O1, Iz, Oz, 135 POz, Pz, CPz, Fpz, Fp2, AF8, AF4, AFz, Fz, F2, F4, F6, F8, FT8, FC6, FC4, FC2, 136 FCz, Cz, C2, C4, C6, T8, TP8, CP6, CP4, CP2, P2, P4, P6, P8, P10, P08, P04, O2 137 as well as the left and right mastoid. The CMS (Common Mode Sense) and DRL 138 (Driven Right Leg) electrodes were used as reference and ground electrodes. 139 Vertical and horizontal electroculogram (EOG) were recorded from electrodes above 140 141 and below the right eye and on the outer canthi of both eyes. EEG and EOG data were continuously recorded at a sampling rate of 1024 Hz. All electrodes were offline 142 re-referenced to the linked mastoids, re-sampled to 512 Hz and filtered with a 0.5 -143 25 Hz band-pass filter. 144

145 Data analysis

Trials were classified according to stimulus congruency (congruent and incongruent), primary task response (correct, error) and secondary task response (correct, early error, late error and I don't know error). For all reported analyses, 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 <i>p</i> -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 (<i>dz</i>) 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 (BF10) 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.*

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

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

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

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

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

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Results

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220 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, *dz* =

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), $t(31) = 10.1$, $p < .001$, $dz =$
227	1.8, 95% $CI = [80.8, 121], BF_{10} = 18850.$
228	
229	Please insert table 1 here
230	
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%), $t(31) = 0.79$, $p = .435$, $dz = 0.14$, 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%), $t(31) = 3.69$, $p = .001$, $dz = 0.66$, 95%
241	$CI = [1.01, 3.11], BF_{10} = 54.65.$
242	A considerable number of errors was categorized as early errors, that is,
243	errors accompanied by early error sensations. Figure 1 shows the relative
244	frequencies of objective errors categorized as early, late and I-don't-know errors
245	among all detected errors. Importantly, the proportion of I-don't-know errors was

247 = 0.23, p = .818, dz = 0.04, 95% CI = [-3.73 4.68], BF₁₀ = 2.98. The frequencies of

15.3% (SE = 4.3%), and was comparable for congruent and incongruent stimuli, t(31)

early and late errors were subjected to an ANOVA with the variables congruency

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

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

274	= 760 ms; SE = 140 ms) errors, $t(26) = 1.95$, $p = .062$, $dz = .375$, 95% $CI = [-13.66, -10.05]$
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.
277	
278	Please insert Figure 1 here
279	
280	ERP Data.
281	Ne/ERN. Waveforms from electrode Fz (Fig. 2A) revealed more negative
282	amplitudes on error trials compared to correct trials shortly after the response. Scalp
283	topographies reflecting the maximum amplitude difference between correct and error
284	trials show a typical fronto-central distribution in both error types. These Ne/ERNs
285	were reliable and significant for early errors (maximum error minus correct difference
286	amplitude: -5.85 µV, SE = 0.76 µV), $t(26) = 7.78$, $p < .001$, $dz = 1.49$, 95% CI = [-
287	7.41, -4.31], BF_{10} = 39416, as well as for late errors (-7.78 µV, SE = 1.26 µV), $t(26)$ =
288	6.25, $p < .001$, $dz = 1.2$, 95% $CI = [-10.33, -5.22]$, $BF_{10} = 16558$. However, a
289	comparison between the two error types revealed no significant difference for the
290	amplitudes, neither for the maximum difference amplitude, $t(26) = 1.76$, $p = .096$, dz
291	= 0.33, 95% CI = [-0.36, 4.21], BF_{10} = 0.93, nor for the mean difference amplitude
292	(early errors = -3.60 μ V, SE = 0.79 μ V; late errors = -4.227 μ V, SE = 0.62 μ V), <i>t</i> (26) =
293	0.836, <i>p</i> = .411, <i>dz</i> = 0.16, <i>95% CI</i> = [-0.92, 2.18], <i>BF</i> 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 < 100.001, $np^2 = .438$ with reliable Ne/ERNs for both error types (early errors = -0.70 μ V, SE = 0.77 μ V, t(26) = 5.756, p < .001, dz = 1.11, 95% CI = [-4.54, -2.15], $BF_{10} = 5456$; late errors = -1.59 μ V, SE = 0.56 μV, *t*(26) = 5.33, *p* < .001, *dz* = 1.02, 95% *CI* = [-5.87, -2.60], *BF* = 2102) compared to correct responses (2.65 μ V, SE = 0.72 μ 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.

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

Pe. In addition, we also compared early and late errors with respect to the Pe, 321 a component that has more frequently been associated with error awareness. 322 Waveforms from electrode Pz (Fig. 2B) revealed more positive amplitudes on error 323 trials than on correct trials starting at around 200 ms after the response. Scalp 324 topographies representing this difference show a posterior distribution for both error 325 types, which is typical for the Pe. The Pe was reliable and significant for early errors 326 (error minus correct: 8.62 μ V, SE = 1.11 μ V), t(26) = 7.76, p < .001, dz = 1.49, 95% 327 $CI = [6.33, 10.9], BF_{10} = 37909$ as well as for late errors (7.11 μ V, SE = 1.32 μ V), 328 t(26) = 5.36, p < .001, dz = 1.03, 95% Cl = [4.39, 9.83], BF₁₀ = 2251. Crucially, a 329 comparison between the two error types revealed a significant difference in the Pe 330 time window as larger Pe amplitudes for early errors were found for the mean 331 difference between correct trials and errors, t(26) = 2.42, p = .023, dz = 0.47, 95% CI 332 = [0.22, 2.79], $BF_{10} = 3.24$. For the maximum difference between correct trials and 333 errors, no significant difference was found neither for the amplitude (early errors: 12.2 334 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 = 335 0.18, 95% CI = [-1.71, 1.87], $BF_{10} = 3.79$ nor for the latencies (early errors: 317 ms, 336 SE = 12 ms; late errors: 301 ms, SE = 13 ms), t(26) = 1.48, p = .151, dz = 0.284, 337

338
$$95\%$$
 Cl = [-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
344	
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 μ V, SE = 0.43 μ V; late errors P1
349	amplitude: 1.59 μV, SE = 0.68 μV; <i>t</i> (26) = 0.72, <i>p</i> = .477, <i>dz</i> = 0.09, <i>95% Cl</i> = [-
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; <i>t</i> (26) = 0.76, <i>p</i> = .451, <i>dz</i> = 0.08, <i>95% Cl</i> = [-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 μ V, SE = 1.18 μ V; <i>t</i> (26) = 0.52, <i>p</i> = .604, <i>dz</i> = 0.12, <i>95%</i>
354	<i>CI</i> = [-1.07, 1.81], <i>BF</i> ₁₀ = 3.34; early errors N1 latency: 151 ms, SE = 3.91 ms; late
355	errors N1 latency: 156 ms, SE = 4.74 ms; <i>t</i> (26) = 0.79, <i>p</i> = .431, <i>dz</i> = 0.08), 95% Cl =
356	$[-14.98, 6.59], BF_{10} = 2.82.$
357	

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], BF₁₀ = 2.71

360

Discussion

Early error sensation is the subjective experience of becoming aware of an 361 error even before the erroneous response was actually executed (Di Gregorio et al., 362 2020). The present data indicate that early error sensations are a frequent and robust 363 phenomenon also in the current study. Replicating a previous work (Di Gregorio et 364 al., 2020), behavioral results showed that participants consistently reported early 365 error sensations on error trials in a similar proportion for congruent and incongruent 366 conditions. Moreover, as in the previous study, no RT difference between early and 367 late errors was obtained. Thus, whether or not participants report an early error 368 sensation did not depend on task-related features like congruency or RT. This is 369 interesting as previous studies speculated that response conflict could influence 370 conscious error detection (Yeung et al., 2004). However, the similar RTs for both 371 error types and the absence of a robust congruency effect here and in a previous 372 study (Di Gregorio et al., 2020) on the frequency of early errors suggests that pre-373 response conflict (i.e., conflict induced by the congruent or incongruent stimulus) did 374 not differ between early and late errors. This speaks against the idea that pre-375 response conflict is directly involved in the generation of early error sensations. 376 Our ERP data revealed several signatures of early error sensations. First of 377

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).

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

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

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

419

Early error sensations as a metacognitive illusion?

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

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

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

458 Conclusion

The present study demonstrated that the time course of the Ne/ERN is 459 predictive of whether an error is perceived as being detected before the occurrence 460 of a response, a phenomenon we called early error sensation. This shows that 461 characteristics of the Ne/ERN can influence error awareness, but also that 462 metacognitive content is sensitive to this early error-related brain activity. We 463 interpret this finding as reflecting the subjective backdating of error awareness to the 464 time point of the Ne/ERN, which resembles similar phenomena in perceptual 465 awareness (Libet et al., 1979) and the emergence of agency (Haggard, Clark, et al., 466 2002). 467 468

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- 613

614	Author contribution.
615	All authors contributed to the study design and study concept. Testing and data
616	collection were performed by FDG and MEM. FDG performed the data analysis and
617	interpretation under the supervision of MS and MEM. FDG drafted the manuscript,
618	and MS and MEM provided critical revisions. All authors approved the final version of
619	the manuscript for submission.
620	
621	
622	Author note.
623	Authors declare no competing interests.
624	

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

		Primary Task				
		Cong	Congruent		gruent	
		Correct	Error	Correct	Error	
Secondary	Correct	99.1 (0.3)	6.81 (3.1)	97.3 (0.6)	8.1 (2.6)	
Task	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)	
Notes: B	rackets contai	n standard er	rors of the mea	n.		
		Figure	Captions			
Figure	1. Behavioral	Idata A Rol	ative frequenci	es of errors clas	ssified as	
early late and	I I-don't-know	errors separa	ately for condru	ent and incond	ruent	
condition. B.	Response time	es for correct r	esponses, earl	v errors and lat	e errors in the	
incongruent c	ondition. ms =	milliseconds.	Error bars repi	resent standard	errors of the	
mean.			·			
Figure	2: Response	locked ERP	data. A Grand	average respo	nse-locked	
ERP waveforr	ns at Fz and w	aveforms of t	he difference b	etween errors a	and correct	
triais. Topogra	aphies represe	nt the negativ	e peak in the e	error minus corr	aray bar	
hetween 0-20	0 ms) Bar ara	nhs represen	t the difference	s (errors minus	corrects) in	
Ne/FRN nega	tive neak amn	litude and late	ency B Grand	averade respor	se-locked	
ERP waveforr	ns at Pz and w	vaveforms of t	the difference b	etween errors	and correct	
trials. Topogra	aphies represe	nt the mean o	of the error min	us correct differ	rence	
waveforms in	the Pe time wi	ndow in each	error condition	i (shaded gray l	bar between	
200-400 ms).	Bar graphs rep	present the di	fference (errors	s minus corrects	s) in the Pe	
amplitude. Th	e horizontal bl	ack arrow rep	resents the tim	e shift of the m	aximal	
Ne/ERN differ	ence between	error types. F	R = response; (CR = correct res	sponse; $\mu v =$	
microvolt; ms	= milliseconds	E Error bars re	epresent the sta	andard error of	the mean.	
Figure	3 stimulus_l	ocked FRP d	ata 🗛 Granda	average stimulu	is-locked	
FRPs waveforms at electrode Fz for Stimulus-locked Ne/FRN analyses (shaded drav						
bar between 250-450 ms). and B waveforms at electrode Oz for P1 (shaded grav bar						

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