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Running head: Early error sensations

Are errors detected before they occur? Early error  
sensations revealed by metacognitive judgments  
on the timing of error awareness

Francesco Di Gregorio<sup>1,2</sup>, Martin E. Maier<sup>1</sup> & Marco Steinhauser<sup>1</sup>

<sup>1</sup>Catholic University of Eichstätt-Ingolstadt, Germany

<sup>2</sup>Casa Dei Risvegli Luca De Nigris - Centro Studi per la Ricerca sul Coma, Bologna, Italy

Correspondence should be addressed to:

Francesco Di Gregorio

Catholic University of Eichstätt-Ingolstadt

Ostenstraße 27

85072 Eichstätt

Germany

E-mail: francesco.digregorio@ku.de

Phone: +int (0)8421-93-21364

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## Introduction

3           Research on human performance monitoring has shown that errors in choice tasks are  
4 detected fast and reliably. For instance, if participants have to classify stimuli under high time  
5 pressure, occasional errors are almost always recognized and can be corrected within a few  
6 hundreds of milliseconds (Rabbitt, 1968, 2002). Frequently, participants in these experiments  
7 report that they sometimes became aware of their errors even slightly before the erroneous  
8 response was executed. Similar observations can be made in everyday behavior. For example,  
9 when writing an email in a hurry, we sometimes have the feeling that an error is about to  
10 occur even before an actual typo is made. These anecdotal reports of early error sensations,  
11 that is, subjective feelings of early error detection, stand in stark contrast to findings from  
12 research on the neural basis of error detection. Here, the predominant view is that correlates of  
13 conscious error detection emerge not until several hundreds of milliseconds after the  
14 erroneous response (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Steinhauser &  
15 Yeung, 2010). The present study aimed to test whether anecdotal evidence of early error  
16 sensations can be corroborated in a controlled study in which participants were asked to  
17 indicate whenever this early error detection has occurred. Robust evidence for early error  
18 sensations would pose strong constraints on theoretical accounts of the emergence of  
19 conscious error awareness.

20           The time course of error detection has frequently been investigated using event-related  
21 potentials (Gehring, Goss, Coles, Meyer, & Donchin, 2018; Ullsperger, Fischer, Nigbur, &  
22 Endrass, 2014). Corresponding studies revealed that errors in choice tasks elicit a cascade of  
23 error-related brain activity that starts almost immediately after the erroneous response. Within  
24 50 to 100 ms after the error, a so-called error-related negativity (Ne or ERN; Falkenstein,  
25 Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993) is  
26 observed, which is supposed to reflect the rapid detection of a mismatch, conflict, or

27 prediction error indicating a discrepancy between the correct and the executed response  
28 (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Holroyd & Coles, 2002; Yeung,  
29 Botvinick, & Cohen, 2004). This Ne/ERN is followed by an error positivity (Pe; Falkenstein  
30 et al., 1991; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005) which emerges about 300 ms  
31 after the error.

32         Several studies investigated how the Ne/ERN and Pe are involved in the emergence of  
33 conscious error detection by asking participants to press a key whenever an error has occurred  
34 or to rate the subjective confidence that they have made an error on each trial. Most  
35 frequently, it has been found that the late Pe but not the early Ne/ERN is predictive of  
36 conscious error awareness or confidence (Boldt & Yeung, 2015; Nieuwenhuis et al., 2001;  
37 Overbeek et al., 2005; Steinhauser & Yeung, 2010). Although the Ne/ERN was larger for  
38 detected errors than for undetected errors in some studies (for a review, see Wessel, 2012), it  
39 has been argued that this reflects differences in intrinsic features of task performance, such as  
40 response conflict, between detected and undetected errors (Steinhauser & Yeung, 2010). This  
41 receives support from the finding that the Ne/ERN can be larger for errors associated with a  
42 lower degree of conscious awareness (Di Gregorio, Steinhauser, & Maier, 2016), and that the  
43 Pe and error awareness can still occur under conditions where the Ne/ERN is impaired or  
44 even absent (Di Gregorio, Maier, & Steinhauser, 2018; Maier, Di Gregorio, Muricchio, & di  
45 Pellegrino, 2015). These results strongly suggest that the later Pe rather than the earlier  
46 Ne/ERN is the neurophysiological correlate of conscious error detection, and that conscious  
47 error detection emerges not until several hundreds of milliseconds after an error. This  
48 conclusion receives further support from the observation that the ability to indicate own errors  
49 is already impaired when the interval between a response and a subsequent stimulus is shorter  
50 than 800 ms (Rabbitt, 2002).

51           Based on these considerations, it becomes clear that there is a discrepancy between  
52 current findings on the time course of error awareness and the anecdotal reports of early error  
53 sensations in experiments. Although conscious error detection emerges several hundred  
54 milliseconds after the error, participants in experimental studies frequently report that they  
55 already knew that a response would be an error before they actually executed it. This apparent  
56 contradiction can be explained in at least two ways: First, it is possible that the Pe is not the  
57 neural correlate of error awareness as frequently assumed, but that error awareness emerges  
58 much earlier. Second, early error sensations could be a metacognitive illusion that serves to  
59 temporally synchronize metacognitive content (error awareness) with objective events (the  
60 erroneous response). Indeed, similar mechanisms have been proposed in the field of visual  
61 awareness. The conscious perception of a visual stimulus has been suggested to emerge at  
62 around 300 ms after presentation of this stimulus (Dehaene & Naccache, 2001; Sergent,  
63 Baillet, & Dehaene, 2005). The fact that we subjectively attribute the emergence of visual  
64 awareness to the onset of the stimulus has been explained by a backward referral process that  
65 aims to create a coherent perception of the objective world in our stream of consciousness  
66 (Libet, Gleason, Wright, & Pearl, 1983; Libet, Wright, Feinstein, & Pearl, 1979). The present  
67 study did not aim to distinguish between these alternatives. Rather, our goal was to set the  
68 stage for further research by providing first experimental evidence for the existence of early  
69 error sensations.

#### 70           *The present study*

71           In this study, we investigated whether early error sensations exist and whether  
72 participants are able to reliably report it. To this end, we conducted four experiments using  
73 two different experimental approaches. In each experiment, participants had to perform a  
74 *primary task* in which errors could occur. Then, a metacognitive *secondary task* was applied,  
75 in which a) participants had to indicate whether an error in the primary task has occurred and

76 whether it was detected before or after execution of the erroneous response (Experiments 1a  
77 and 1b), or b) participants had to rate the subjective confidence that such an early error  
78 sensation has occurred (Experiment 2a and 2b). The secondary task essentially required  
79 participants to solve a signal detection task. That is, they had to detect a signal (the early error  
80 sensation) among noise. The standard framework for analyzing tasks like this is signal  
81 detection theory (Green & Swets, 1966) or its applications to metacognitive judgments  
82 (Maniscalco & Lau, 2012). Within all these frameworks, the ability to detect a signal is  
83 quantified based on the rates of correctly and falsely detected signals (i.e., hits and false  
84 alarms). However, the particular challenge in the present case is that we cannot discriminate  
85 between hits and false alarms, as we do not know for which errors early error sensations are  
86 present or whether early error sensations exist at all. It is possible that participants simply  
87 report early error sensations because they are instructed to do so, thus forming expectations  
88 about its existence or its frequency. In other words, the data could reflect an instruction bias  
89 or an expectation bias rather than real signal detection.

90 To deal with this problem, we adopted several experimental strategies: First, we  
91 measured early error sensations using different tasks and methods. In Experiments 1a and 1b,  
92 the primary task was a flanker task (Eriksen & Eriksen, 1974) and the secondary task required  
93 participants to simply indicate whether an early error sensation had occurred or not. In  
94 Experiment 2a and 2b, the primary task was a letter/number discrimination task and the  
95 secondary task employed post-decision wagering (Persaud, McLeod, & Cowey, 2007), a  
96 method that has been proposed as an effective measure of visual awareness (Persaud et al.,  
97 2007) or metacognitive content (Seth, 2008). Finding similar rates of early error sensations  
98 across different primary and secondary tasks would speak for the robustness of this  
99 phenomenon. Second, we aimed to improve metacognitive judgments on early error  
100 sensations by introducing a second task that served as a reference point for judgments on early

101 error sensations. Although post-decision wagering has been assumed to generally improve  
102 judgments about the contents of consciousness (Persaud et al., 2007; Seth, 2008), participants  
103 may not have an objective criterion to judge whether early error sensations have actually  
104 occurred. Thus, we sought to provide a reference point to guide participants' metacognitive  
105 judgments. Participants initially performed a task involving metacognitive judgments on their  
106 response accuracy in a Visual Awareness task. In the subsequent main task, they were  
107 instructed that their reports of early error sensations should be based on the same level of  
108 confidence as their previous judgments in the Visual Awareness task. Moreover, we directly  
109 investigated the impact of expectations on reports of early error sensations. We varied the  
110 difficulty of the initial Visual Awareness task across Experiments 2a and 2b, and asked  
111 whether the pattern of metacognitive judgments in this task is carried over to the pattern of  
112 reports of early error detection in the main task, thus indicating an expectation bias.

### 113 **Experiment 1**

114 The goal of the first experiment was to study whether and how frequently participants  
115 report early error sensations in a flanker task – one of the most frequently used tasks in studies  
116 on error detection. On each trial, participants first had to perform a flanker task in which they  
117 responded to the direction of a central target arrow (left/right) while ignoring congruent or  
118 incongruent distractor arrows. Here, errors mainly occur on incongruent trials. Then,  
119 participants had to classify their responses according to whether they were correct, or whether  
120 an early error (detected before response execution) or a late error (detected after response  
121 execution) occurred. Because participants in Experiment 1a frequently reported that they were  
122 unsure about when an error was detected, we conducted Experiment 1b in which they could  
123 additionally indicate that they did not know whether error detection occurred early or late.

124 We were primarily interested in whether a substantial amount of error trials show early  
125 error sensations. If early error sensations reflected a metacognitive illusion resulting from the



126 synchronization of metacognitive content with objective motor events, the frequency of this  
127 phenomenon should be rather high. In addition, we also compared early and late errors with  
128 respect to their response time (RT) as this could provide valuable information about the  
129 source of early error sensations. If early error sensations reflected the described metacognitive  
130 illusion, there is no reason to assume that early and late errors differ with respect to RT. If,  
131 however, early error sensations represented the true time course of error detection relative to  
132 the response, we might observe a relation between RT and the subjective timing of error  
133 awareness, which could emerge for different reasons: First, early errors could occur mainly on  
134 trials with slow RTs, i.e., when the motor command was delayed and sent after error detection  
135 has already occurred (e.g., based on the preceding decision process). Second, early errors  
136 could occur mainly on trials with fast RTs, as studies on the latency of error detection have  
137 found that lower response criteria (i.e., less cautious responding) lead to both shorter RTs and  
138 shorter latencies of error detection (Steinhauser, Maier, & Hübner, 2008).

### 139 *Method*

140 *Participants.* 23 participants (4 male) between 19 and 29 years of age ( $M = 21.8$ ,  $SE =$   
141  $0.6$ ) participated in Experiment 1a. A new group of 20 participants (6 male) between 19 and  
142 28 years of age ( $M = 22.1$ ,  $SE = 0.58$ ) participated in Experiment 1b. All participants had  
143 normal or corrected to normal vision, were recruited from the student population at the  
144 Catholic University of Eichstätt-Ingolstadt, and received course credit or 8 Euro per hour for  
145 participation. The study was approved by the ethical committee of the Catholic University of  
146 Eichstätt-Ingolstadt, and informed consent was obtained from all participants.

147 *Apparatus.* A PC running presentation software (Neurobehavioral Systems, Albany,  
148 CA) controlled stimulus presentation and response registration. Stimuli were presented on a  
149 21-inch color monitor (60 Hz refresh rate) at a viewing distance of 70 cm.

150 *Task and procedure.* Both experiments consisted of a primary task in which  
151 participants performed a flanker task and a secondary task in which participants classified  
152 their response on the primary task. Stimuli of the flanker task were strings of five arrow heads  
153 (e.g., < < > < <) in Arial font, subtending a visual angle of 4.1° horizontally and 1.4°  
154 vertically. The central arrow head in each string was designated as the target and the lateral  
155 arrows were designated as the flankers. Flankers could have either the same direction as the  
156 target (*congruent* condition) or the opposite direction (*incongruent* condition).

157 Each trial started with the presentation of a fixation cross for 350 ms. Then, the  
158 stimulus of the flanker task was presented for 200 ms followed by a black screen until a  
159 response was given. Participants had to identify the direction of the target by pressing the “left  
160 arrow” key or the “right arrow” key on a standard keyboard with the index or the middle  
161 finger of the right hand (*primary task response*). After the response, another black screen was  
162 presented for 1000 ms. Then, a question mark appeared in the screen center to prompt  
163 participants to classify their response in the primary flanker task. To this end, participants had  
164 to execute one of three classification responses on the same keyboard with the left hand  
165 (*secondary task response*). Participants indicated whether a) they felt they had responded  
166 correctly (“A” key with ring finger), b) they felt they had committed an error (i.e., they  
167 pressed the wrong button on the primary task), and this feeling has emerged already before  
168 actual response execution (early error; “S” key with middle finger), or c) they had committed  
169 an error without this early error sensation (late error; “D” key with index finger). In  
170 Experiment 1b, a fourth response alternative could be provided to indicate if they detected an  
171 error but did not know whether this was detected before or after the error was committed (“F”  
172 key, also with index finger).

173 Both experiments consisted of eight test blocks with 64 trials per block. Each block  
174 contained 16 instances of each of the four possible flanker stimuli in randomized order. Prior

175 to the test blocks, participants performed two practice blocks (32 trials each) without a  
176 secondary response to practice the primary task, and two further practice blocks (32 trials  
177 each) in which the secondary task response was introduced. In all practice blocks, whenever  
178 the error rate in the preceding block was below 25%, participants were instructed to respond  
179 faster on the primary task prior to the next block. Before the secondary task was introduced,  
180 participants were instructed about early error sensations. We told participants that errors are  
181 sometimes accompanied by the sensation that they already knew that they commit an error  
182 before the incorrect button was pressed, and that this is called “early error sensation”. In other  
183 words, participants were instructed not only to report errors, but also to focus on the timing of  
184 error detection. Similar instructions were used to introduce early error sensation in all  
185 experiments.

186 *Data analysis.* Trials were classified according to stimulus congruency (congruent,  
187 incongruent), primary task response (correct, error), and secondary task response (correct,  
188 early error, late error – in both experiments - and I don’t know error in Exp. 1b). RT in the  
189 primary task was defined as the time interval between the onset of the stimulus and the  
190 subsequent button press. To control for outliers, trials were excluded whenever the response  
191 time of the primary task response was 3 standard deviations above or below the condition  
192 mean (<1%). All frequency data were arcsine transformed before statistical analyses (Winer,  
193 1971).

194 Data were analyzed using analyses of variance (ANOVAs) with repeated measurement  
195 and planned comparisons using two-tailed t-tests for dependent samples. To compensate for  
196 violations of sphericity, Greenhouse–Geisser corrections were applied whenever appropriate  
197 (Greenhouse & Geisser, 1959), and corrected p values (but uncorrected degrees of freedom)  
198 are reported.

199



201 *Table 1: Experiments 1a and 1b.* Relative frequencies (in %) of secondary task  
 202 responses for each stimulus condition and primary task response. Please note that the error  
 203 rate cannot be derived from this table as these frequencies reflect secondary task responses  
 204 only.

		Primary Task			
		Congruent		Incongruent	
		Correct	Error	Correct	Error
Secondary Task (1a)	Correct	99.66 (0.1)	0.96 (0.53)	98.4 (0.5)	3.26 (0.64)
	Early Error	0.25 (0.1)	66.7 (7.9)	1.01 (0.4)	69.1 (3.5)
	Late Error	0.09 (0.04)	32.3 (7.9)	0.61 (0.13)	27.7 (3.5)
Secondary Task (1b)	Correct	98.8 (1.7)	2.91 (1.24)	97.9 (0.5)	3.75 (0.74)
	Early Error	0.76 (0.43)	61.45 (7.04)	0.89 (0.45)	57.2 (6.1)
	Late Error	0.12 (0.07)	28.88 (7.51)	0.17 (0.09)	28.4 (5.4)
	Don't know	0.29 (0.11)	6.76 (2.88)	1.02 (0.25)	10.7 (3.2)

205 Notes: Brackets contain standard errors of the mean.

206

## 207 *Results*

208 *Experiment 1a.* In a first step, we analyzed the overall performance in the primary  
 209 flanker task. The mean error rate was 1.68% (SE = 0.49%) for congruent errors and 13.8%  
 210 (SE = 2%) for incongruent errors (corresponding to 6.6 errors for congruent trials and 54.5  
 211 errors for incongruent trials). A t-test on the frequency data showed a congruency effect,  $t(22)$   
 212 = 9.89,  $p < .001$ ,  $d = 2.11$ . We also investigated the congruency effect in RTs by comparing  
 213 correct trials in the congruent and incongruent conditions. Statistical analyses showed a  
 214 standard congruency effect with faster RTs for congruent corrects (M = 378 ms, SE = 8 ms)  
 215 than incongruent corrects (M = 478 ms, SE = 14 ms),  $t(22) = 11.44$ ,  $p < .001$ ,  $d = 2.38$ .

216 We then considered the frequencies of secondary task responses for each primary task  
217 response and stimulus condition (see Tab. 1). As observed in previous studies (e.g.,  
218 Steinhauser, Maier, & Hübner, 2008), the mere detection of errors (independent of error type)  
219 was very reliable. 97.8% (SE = 0.6%) of objective errors were categorized as either early  
220 errors or late errors, and this rate was higher for congruent stimuli (M = 99.1%, SE = 0.52%)  
221 than for incongruent stimuli (M = 96.7%, SE = 0.64%),  $t(22) = 2.71, p = .012, d = 0.57$ . Only  
222 0.9% (SE = 0.01%) of correct responses were categorized as errors, which was also higher for  
223 incongruent (M = 1.63%, SE = 0.5%) than for congruent stimuli (M = 0.34%, SE = 0.12%),  
224  $t(22) = 3.08, p = .005, d = 0.64$ .

225 Crucially, a considerable number of errors was categorized as early errors, that is, as  
226 errors accompanied by an early error sensation. Figure 1A shows the proportion of objective  
227 errors categorized as early and late errors among all detected objective errors. The proportion  
228 of early errors was similar for congruent (M = 76.1%, SE = 5.1%) and incongruent trials (M =  
229 71.4%, SE = 4%),  $t(22) = 0.96, p = .347, d = 0.21$ . Additionally, we calculated confidence  
230 intervals (CI) to show the range of frequencies of early errors. The 95%-CIs ranged from  
231 65.4% to 86.9% for congruent trials and between 63.9% and 78.9% for incongruent trials.

232 Additionally, we investigated the RTs of the different error types. Only incongruent  
233 trials were considered for this analysis because 12 participants had no errors in at least one  
234 condition of the congruent trials. Moreover, only correct trials classified as correct and error  
235 trials classified as errors were entered into this analysis. The mean number of trials included  
236 was 143.3 (SE = 5.0) for correct trials, 41.1 (SE = 6.9) for early errors, and 16.0 (SE = 3.2) for  
237 late errors. The results of the one-way ANOVA (corrects, early error, late error) showed a  
238 significant effect,  $F(2,44) = 5.86, p = .022, \eta_p^2 = .21$ . Planned contrasts revealed larger RTs  
239 for correct trials (M = 474 ms, SE = 13 ms) than for early errors (M = 367 ms, SE = 15 ms),  
240  $t(22) = 12.1, p < .001, d = 2.52$ , but no significant difference between correct trials and late

241 errors ( $M = 448$  ms,  $SE = 46$  ms),  $t(22) = 0.68$ ,  $p = .51$ ,  $d = 0.14$ . Furthermore, the difference  
242 between early and late errors was marginally significant,  $t(22) = 2.07$ ,  $p = .051$ ,  $d = 0.42$ .

243

244 *Experiment 1b.* The data were analyzed in the same way as in Experiment 1a. In the  
245 primary task, the mean error rate was smaller for congruent errors ( $M = 5.56\%$ ,  $SE = 1.58\%$ )  
246 than for incongruent errors ( $M = 27.8\%$ ,  $SE = 2.4\%$ ),  $t(19) = 8.49$ ,  $p < .001$ ,  $d = 1.89$ . RTs  
247 were faster for congruent correct trials ( $M = 378$  ms,  $SE = 8$  ms) than for incongruent correct  
248 trials ( $M = 463$  ms,  $SE = 12$  ms),  $t(19) = 10.2$ ,  $p < .001$ ,  $d = 2.34$ .

249 Frequencies of secondary task responses (Tab. 1) again revealed that the detection of  
250 errors (independent of error type) was very reliable. 96.6% ( $SE = 0.93\%$ ) of objective errors  
251 were categorized as either early errors, late errors or I don't know errors, and this rate was  
252 comparable between congruent stimuli ( $M = 97.1\%$ ,  $SE = 1.23\%$ ) and incongruent stimuli ( $M$   
253  $= 96.3\%$ ,  $SE = 0.73\%$ ),  $t(19) = 0.61$ ,  $p = .55$ ,  $d = 0.13$ . Only 1.63% ( $SE = 0.5\%$ ) of correct  
254 responses were categorized as errors, which was higher for incongruent ( $M = 2.08\%$ ,  $SE =$   
255  $0.51\%$ ) than for congruent stimuli ( $M = 1.17\%$ ,  $SE = 0.44\%$ ),  $t(19) = 3.49$ ,  $p = .002$ ,  $d = 0.78$ .

256 Crucially, the results again showed that participants consistently reported errors  
257 accompanied by early error sensations (Fig. 1B). In this experiment, participants could  
258 classify their errors as I don't know errors if they felt unable to classify them as early or late  
259 errors. However, the proportion of these errors was low ( $M = 9.03\%$ ,  $SE = 3.15\%$ ; 95%-CI =  
260  $7.55\% - 10.5\%$ ), and comparable for congruent and incongruent stimuli,  $t(19) = 1.05$ ,  $p = .31$ ,  
261  $d = 0.23$ . Due to this third category, we could now analyze the proportion of early and late  
262 errors in an ANOVA with the variables congruency (congruent, incongruent) and error type  
263 (early errors, late errors). This analysis revealed a significant main effect of error type,  
264  $F(1,19) = 6.62$ ,  $p = .019$ ,  $\eta_p^2 = .25$ , indicating that early errors ( $M = 59.1\%$ ,  $SE = 7.08\%$ ;  
265 95%-CI =  $55.8\% - 62.4\%$ ) were more frequent than late errors ( $M = 29.4\%$ ,  $SE = 6.69$ ; 95%-

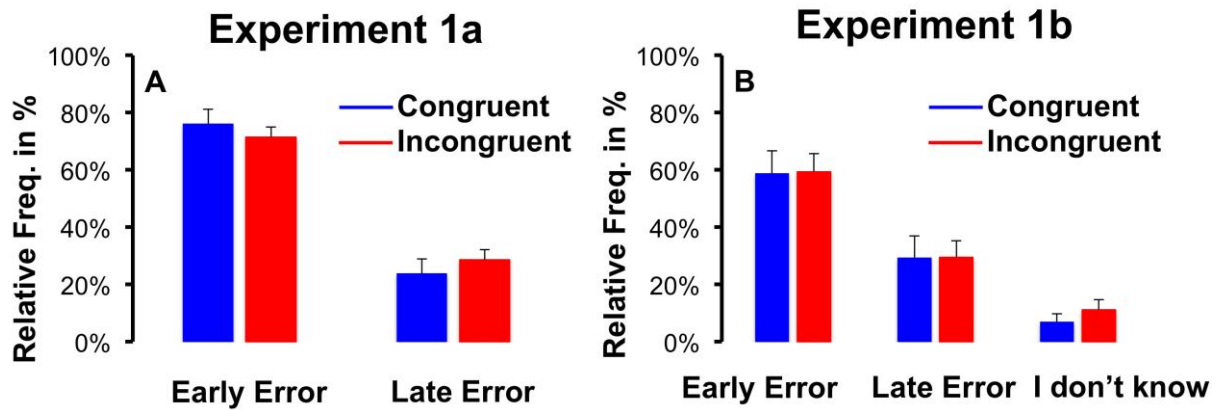
266 CI = 26.3% - 32.5%). However, neither a significant main effect of congruency,  $F(1,19) =$   
267  $0.321, p = .861, \eta_p^2 = .02$ , nor a significant interaction,  $F(1,19) = 0.321, p = .861, \eta_p^2 = .02$ ,  
268 was obtained.

269 Finally, we investigated RTs for correct responses, early and late errors. Again, only  
270 incongruent trials were considered for this analysis because 13 participants had no error trials  
271 in at least one condition of the congruent trials. Moreover, in line with Experiment 1a, only  
272 correct trials classified as correct and error trials classified as errors were entered into this  
273 analysis. The mean number of trials included was 209.0 (SE = 7.5) for correct trials, 47.5 (SE  
274 = 6.6) for early errors, and 23.1 (SE = 4.0) for late errors. The results of the one-way ANOVA  
275 (corrects, early error, late error) showed a significant effect,  $F(2,38) = 159, p < .001, \eta_p^2 = .89$ .  
276 RTs were larger for correct trials (M = 463 ms, SE = 12 ms) than for the other two error types,  
277  $ts > 13.2, ps < .001, ds > 2.95$ . Nevertheless, there was no significant difference between early  
278 (M = 358 ms, SE = 10 ms) and late errors (M = 353 ms, SE = 13 ms),  $t(19) = 0.71, p = .486, d$   
279  $= 0.16$ .

280 *Comparison of Experiments 1a and 1b.* In a last step, we compared frequencies of  
281 early errors (among all errors) in the congruent and incongruent conditions between  
282 Experiments 1a and 1b. The resulting mixed-model ANOVA with the within-participant  
283 variable congruency and the between-participant variable Experiment showed a significant  
284 effect of Experiment indicating a lower overall frequency of early errors in Experiment 1b (M  
285 = 59.1%, SE = 7.1%) compared to Experiment 1a (M = 73.7%, SE = 4.5%),  $F(1,41) = 4.31, p$   
286  $= .044, \eta_p^2 = .095$ . Notably, this analysis revealed neither a significant main effect of  
287 congruency,  $F(1,41) = 0.26, p = .607, \eta_p^2 = .006$ , nor a significant interaction,  $F(1,41) =$   
288  $0.414, p = .524, \eta_p^2 = .01$ .

289





291 *Figure 1: Data from Experiments 1a and 1b. A: Proportion of errors classified as early*  
 292 *or late in the congruent and incongruent conditions for Experiment 1a. B: Proportion of errors*  
 293 *classified as early, late or I don't know in the congruent and incongruent conditions for*  
 294 *Experiment 1b. Error bars represent standard errors of the mean.*

### 296 *Discussion*

297 Data from Experiment 1 showed that our task successfully evoked reports of early  
 298 error sensations and participants reported this feeling on a substantial proportion of error  
 299 trials. Subjective reports on early error sensations were independent from other task-related  
 300 features like stimulus congruency and RT. Indeed, participants reported early error sensations  
 301 in a similar proportion for congruent and incongruent errors in both Experiments 1a and 1b.

302 In Experiment 1a, participants had to guess whenever they did not know when they  
 303 detected the error. By adding a fourth classification response (I don't know), this effect of  
 304 guessing was controlled in Experiment 1b. As a result, the proportion of early detected errors  
 305 decreased from 76% in Experiment 1a to 59% in Experiment 1b, which presumably reflects  
 306 that participants frequently classified errors as early detected errors when they were actually  
 307 unsure about when the error was detected. Introducing the "I don't know" category in  
 308 Experiment 1b eliminated this effect suggesting that the 59% early detected errors in  
 309 Experiment 1b provides a more valid estimate of the true proportion of trials with early error  
 310 sensations. Furthermore, the marginally significant difference in RTs between early and late

311 errors in Experiment 1a was absent in Experiment 1b, which suggests that this difference  
312 reflects that many early errors were indeed guesses in the secondary task, which seem to be  
313 associated with shorter RTs in the primary task.

314 In general, participants reported early errors with a high frequency and we did not find  
315 robust evidence of differences in task-related features (i.e., stimulus congruency or RT)  
316 between early and late errors. Both results could suggest that early error sensations result from  
317 a functionally relevant process that serves to temporally synchronize the execution of the  
318 erroneous action and the later occurring error awareness.

## 319 **Experiment 2**

320 Participants in our first experiments reported that they had detected an error already  
321 before response execution on the majority of trials. This was the case even when they also  
322 could have classified the error as “I don’t know” in Experiment 1b, suggesting that they  
323 classified the remaining errors as early or late with considerable confidence. However,  
324 because the reported early error sensations are subjective reports on the participants' own  
325 metacognitive contents, there is no objective information about whether an early error  
326 sensation has really occurred. Therefore, it may still be argued that results reflect an  
327 expectation bias. Namely, participants could simply have expected that some errors must have  
328 been early errors, because we instructed them about their existence. In Experiment 2, we  
329 aimed to directly test how confident participants are about early error sensations and if their  
330 reports of early error sensations are subject to an expectation bias.

331 The procedure we used was post-decision wagering. In typical studies using this  
332 method, participants are instructed to perform a challenging perceptual discrimination task  
333 and then are asked how much money they would wager on the correctness of their response  
334 (Persaud et al., 2007). Post-decision wagering is particularly suitable to assess metacognitive  
335 contents as monetary incentives can improve the accuracy of these judgments and wagering

336 provides a direct and intuitive measure to rate subjective confidence associated with a  
337 decision (Persaud et al., 2007; Windey & Cleeremans, 2015). In our Error Awareness task, we  
338 modified this procedure by having participants wager on their early error sensations. More  
339 specifically, after each response, participants had to place one of three bets on whether they  
340 have experienced an early error sensation: No bet, a low bet, or a high bet. Even though we  
341 could not objectively verify participants' bets, we instructed them that their wagering should  
342 correspond to their subjective confidence of having experienced an early error sensation.  
343 While we informed participants that they would not earn any money in this task, they were  
344 not explicitly told that their bets could not be verified.

345         To further improve the participants' metacognitive assessments, we provided a more  
346 objective reference point that should guide their wagering on early error sensations. Prior to  
347 the Error Awareness task, participants performed a Visual Awareness task similar to those  
348 typically used with the post-decision wagering method (Persaud et al., 2007). In this task,  
349 participants first performed a difficult perceptual letter/number discrimination with masked  
350 stimuli and after their response, they wagered on whether they had seen the stimulus, and  
351 hence, on their response accuracy. In the subsequent Error Awareness task, which used the  
352 same stimuli but a longer masking interval, participants were instructed to apply similar levels  
353 of confidence when placing their bets as in the Visual Awareness task. That is, they should  
354 place a high bet only if they were similarly confident of having experienced an early error in  
355 the Error Awareness task as of having executed a correct response in the Visual Awareness  
356 task. In this way, we induced a common metric for the metacognitive judgments in the two  
357 tasks. High bets in the Error Awareness task should be associated with the same confidence as  
358 high bets in the Visual Awareness task, with the advantage that we have objective data on the  
359 accuracy of the latter bets.

360 Finally, this two-stage design allowed us to evaluate the possible impact of  
361 expectation biases on the reports of early error sensations. If participants reported early errors  
362 only because they expected that early error sensations exist, their judgments should be  
363 strongly influenced by the proportion of low and high bets in the preceding Visual Awareness  
364 task. Performance in the Visual Awareness task should serve as an anchor or reference point  
365 for how many low and high bets should be expected, if no objective signal about the timing of  
366 error detection is available. We therefore conducted two experiments (Experiment 2a and 2b)  
367 in which we varied the difficulty of the perceptual discrimination in the Visual Awareness  
368 task. In particular, we calibrated stimulus-masking intervals to set individual response  
369 accuracy to around 75% for Experiment 2a and to around 50% for Experiment 2b. In this  
370 way, we varied perceptual difficulty and thus the number of low and high bets in the Visual  
371 Awareness task, while holding the difficulty of the Error Awareness task constant. If the  
372 reported rate of early error sensations is influenced by the reference point set by the Visual  
373 Awareness task, we should obtain more high bets on early error sensations when the Visual  
374 Awareness task was easier (Exp. 2a) than when it was more difficult (Exp. 2b).

### 375 *Method*

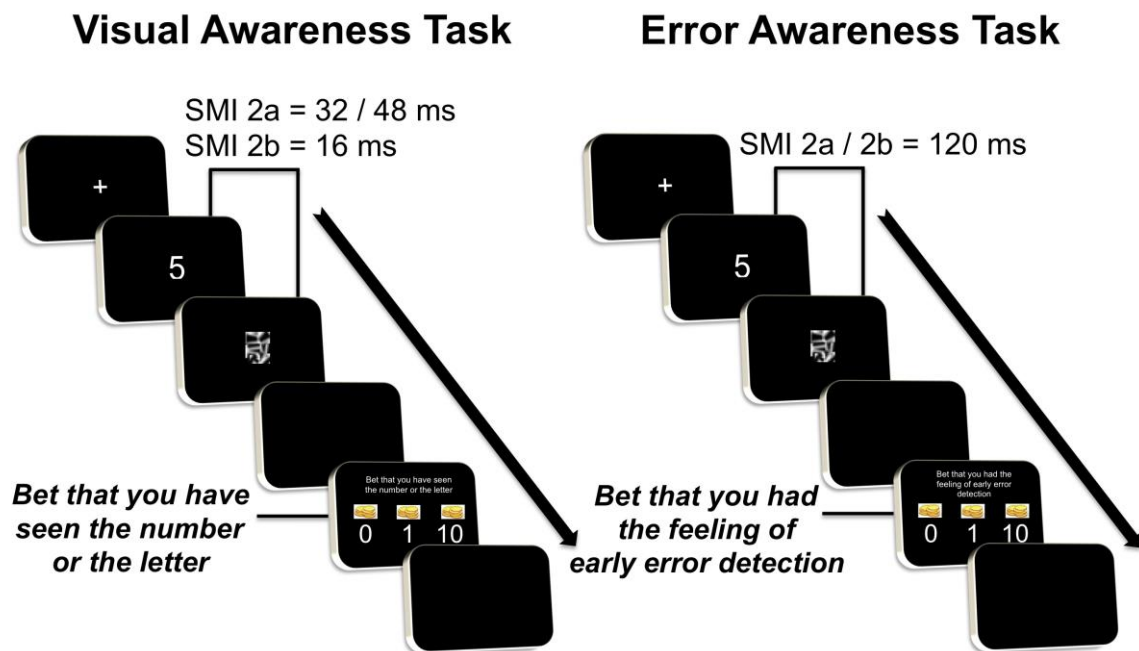
376 *Participants.* 20 participants (3 male), which did not participate in Experiment 1,  
377 between 19 and 26 years of age ( $M = 22.6$ ,  $SE = 0.7$ ) with normal or corrected to normal  
378 vision participated in Experiment 2a. A new group of 20 participants (5 male) between 19 and  
379 31 years of age ( $M = 23.4$ ,  $SE = 0.9$ ) participated in Experiment 2b.

380 *Overview.* Both experiments consisted of two separate sub-tasks, which always  
381 occurred in the same order: Participants first performed a Visual Awareness task and then an  
382 Error Awareness task. In the Visual Awareness task, participants performed a difficult  
383 perceptual discrimination task (primary task), and then wagered 0 cents (no bet), 1 cent (low  
384 bet) or 10 cents (high bet) on the accuracy of the primary task response (secondary task). In

385 the Error Awareness task, participants performed a speeded choice task (primary task), and  
386 then wagered on whether they had the feeling of early error detection in case of an error  
387 (secondary task).

388 *Visual Awareness task.* Each target stimulus was a letter (W, B, G, T, S, C, P, N, or R)  
389 or a number (1, 2, 3, 4, 5, 6, 7, 8, or 9) subtending a visual angle of 0.5° horizontally and 1.4°  
390 vertically and presented in the center of the screen. The procedure of a trial is depicted in  
391 Figure 2. The primary task required participants to classify the target as a letter or a number  
392 by pressing the “left arrow” key or the “right arrow” key with the index or middle finger,  
393 respectively, of the right hand. The category-response mapping was counterbalanced across  
394 participants. Each trial started with the presentation of a fixation cross for 350 ms, which was  
395 followed by the target. After a stimulus-mask interval (SMI, see below), a mask appeared for  
396 200 ms that consisted of random feature patterns created by randomly rearranging features of  
397 the letter and number stimuli. Then, a black screen was presented until a response was  
398 provided. After the response, the German equivalent of the text “Bet that you have seen the  
399 number or the letter: 0 cents, 1 cent, 10 cents” was presented. As secondary task, participants  
400 had to provide one of the three wagering responses (0, 1, 10) on the keyboard with index (D  
401 key), middle (S key) or ring finger (A key), respectively, of the left hand. Participants were  
402 instructed that whenever they responded correctly, they would earn the corresponding  
403 wagered money, and that in case of an error, they would lose the wagered money. After the  
404 response, another black screen was presented for 1500 ms followed by the next trial.

405



406

407 *Figure 2: Procedure in Experiments 2a and 2b.* Procedure of a trial in the Visual  
 408 Awareness task (left side) and the Error Awareness task (right side). SMI 2a and 2b refer to  
 409 the intervals used in Experiment 2a and 2b, respectively. SMI = stimulus-masking interval.  
 410

411 The SMI for Experiment 2a was determined in a pilot study in which 6 participants  
 412 worked only on the Visual Awareness task. The SMI was calibrated using a staircase  
 413 procedure to obtain a mean error rate of 25%. The experiment started with an SMI of 32 ms.  
 414 Whenever participants committed less than 15% of errors in the last 20 trials, the SMI was  
 415 decreased by one step (-16 ms). Whenever participants committed more than 35% of errors in  
 416 the last 20 trials, the SMI increased by one step (+16 ms). The task terminated when a  
 417 constant error rate of 25% was observed in the last 60 trials. The resulting SMI was 32 ms in  
 418 5 participants and 48 ms in 1 participant. Therefore, an SMI of 32 ms was used in Experiment  
 419 2a.

420 Experiment 2a started with two practice blocks (72 trials each) in which the Visual  
 421 Awareness task was practiced and the SMI was re-calibrated for each participant (using the  
 422 same method as in the pilot study and starting with an SMI of 32 ms). The resulting SMIs

423 used in the test blocks were 32 ms for 15 participants and 48 ms for 5 participants. Only in  
424 these practice blocks, participants received feedback about whether they wagered  
425 advantageously (i.e., correct response followed by 10 cents bet and error followed by 0 cents  
426 bet) or not (correct response followed by 1 or 0 cents bet and error followed by 10 or 1 cents  
427 bet). No feedback was provided in the test blocks to make the Visual Awareness task as  
428 similar as possible to the subsequent Error Awareness task in which no feedback was  
429 possible. After these practice blocks, participants completed 6 test blocks (72 trials each). At  
430 the end of all blocks in visual awareness task, participants were informed about the amount of  
431 money they won.

432 In Experiment 2b, we used an SMI of 16 ms for all participants. This was done to  
433 further limit stimulus processing relative to Experiment 2a, and thus, to set a different  
434 reference point for the later Error Awareness task. Manipulating the SMI across Experiments  
435 2a and 2b would allow for studying the impact of an expectation bias on the report of early  
436 error sensations in the Error Awareness Task.

437 *Error Awareness task.* The Error Awareness task in both experiments employed a  
438 similar trial sequence and the same stimuli as the Visual Awareness task (see Fig. 2) but  
439 differed in the SMI, the instruction, and the secondary task. We now used a fixed SMI of 120  
440 ms, which should prevent errors due to data limitation and thus should guarantee that error  
441 detectability is high (Del Cul, Dehaene, Reyes, Bravo, & Slachevsky, 2009; Scheffers &  
442 Coles, 2000). To obtain a mean error rate of 25%, participants were instructed to respond as  
443 quickly as possible. Moreover, whenever the average error rate in a block fell below 20%,  
444 participants were prompted to respond more quickly prior to the beginning of the next block.  
445 The secondary task was to bet on the feeling of early error detection. The equivalent of the  
446 German text was: “Bet that you had the feeling of early error detection: 0 cents, 1 cent, 10  
447 cents”, and participants had to execute one of the three wagering responses (0, 1, 10).

448 Participants were instructed to wager 0 cents in case of correct responses. The Error  
449 Awareness task was always conducted after the last block of the Visual Awareness task. It  
450 consisted of 2 practice blocks and 12 test blocks with 72 trials each. In contrast to the Visual  
451 Awareness task, participants did not receive any money in the Error Awareness task, as there  
452 is no possibility to determine whether a wager was successful or not. Prior to the task,  
453 participants were explicitly instructed to apply similar levels of confidence as in the Visual  
454 Awareness task when placing their bets in the Error Awareness task. Specifically, they were  
455 instructed to place a high bet in the Error Awareness task only if they were similarly confident  
456 of having experienced an early error sensation as of having seen the stimulus (on high-bet  
457 trials) in the Visual Awareness task.

458 *Data analysis.* RTs and frequencies were analyzed in the same way as in Experiment  
459 1. For both the Visual Awareness task and the Error Awareness task, the correctness of the  
460 primary task response and the type of wagering response were used to distinguish the  
461 following trials types: (1) *correct/high bet* on which the response in the primary task was  
462 correct and the wagered amount of money was 10 cents; (2) *correct/low bet* on which the  
463 response in the primary task was correct and the wagered money was 1 cent; (3) *correct/no*  
464 *bet* on which the response in the primary task was correct and the wagered money was 0  
465 cents; (4) *error/high bet* on which the response in the primary task was an error and the  
466 wagered money was 10 cents; (5) *error/low bet* on which the response in the primary task was  
467 an error and the wagered money was 1 cent; (6) *error/no bet* on which the response in the  
468 primary task was an error and the wagered money was 0 cents.

469 *Results*

470 *Experiment 2a: Visual Awareness Task.* Analysis of the primary task response in the  
471 Visual Awareness task indicated a mean error rate of 21.8% (SE = 3.5%), which  
472 corresponded to a mean number of errors of 94.2 (SE = 15.12). Moreover, participants were



473 faster on correct trials ( $M = 904$  ms,  $SE = 77$  ms) than on error trials ( $M = 1302$  ms,  $SE = 122$   
474 ms),  $t(19) = 3.34$ ,  $p = .003$ ,  $d = 0.79$ . Table 2 provides the frequencies for each secondary task  
475 response among correct and error trials. On correct trials, participants had a larger frequency  
476 of advantageous wagering (correct/high bet;  $M = 66.1\%$ ;  $SE = 6.7\%$ ;  $95\%-CI = 62.9\% -$   
477  $69.2\%$ ) compared to correct/low bet ( $M = 25.5\%$ ;  $SE = 5.2\%$ ;  $95\%-CI = 23.1\% - 27.9\%$ ),  
478  $t(19) = 3.51$ ,  $p = .002$ ,  $d = 0.78$ , and a larger frequency of correct/low bet compared to  
479 correct/no bet ( $M = 8.46\%$ ;  $SE = 3.4\%$ ;  $95\%-CI = 6.9\% - 10.1\%$ ),  $t(19) = 3.01$ ,  $p = .007$ ,  $d =$   
480  $0.67$  (see also Figure 3). On error trials, error/low bets ( $M = 40\%$ ;  $SE = 4.7\%$ ;  $95\%-CI =$   
481  $37.8\% - 42.2\%$ ) were more frequent than error/high bets ( $M = 24.7\%$ ;  $SE = 4.1\%$ ;  $95\%-CI =$   
482  $22.8\% - 26.6\%$ ),  $t(19) = 2.53$ ,  $p = .021$ ,  $d = 0.56$ , while error/no bets ( $M = 35.3\%$ ;  $SE = 1.3\%$ ;  
483  $95\%-CI = 34.7\% - 35.9\%$ ) were comparable with error/low bets,  $t(19) = 0.45$ ,  $p = .657$ ,  $d =$   
484  $0.11$ . The considerable number of low bets, particularly on error trials, suggests that data  
485 limitation led to a high response uncertainty. Because the Visual Awareness Task is not a  
486 speeded choice task, and because several participants had only few responses for single  
487 conditions, we did not further analyze RTs as a function of the secondary task response.  
488  
489

490 *Table 2: Experiment 2a and 2b.* Relative frequencies (in %) of secondary task  
 491 responses for each wagering condition and primary task response. Please note that the error  
 492 rate cannot be derived from this table as these frequencies reflect secondary task responses  
 493 only.

		Primary Task			
		Visual Awareness		Error Awareness	
		Correct	Error	Correct	Error
Secondary Task (2a)	High Bet	66.1 (6.7)	24.7 (4.1)	12.3 (6.3)	62.4 (5.8)
	Low Bet	25.5 (5.2)	40 (4.7)	2.44 (0.86)	19.8 (4.2)
	No Bet	8.46 (3.4)	35.3 (1.3)	85.3 (6.5)	17.8 (4.7)
Secondary Task (2b)	High Bet	36.5 (5.1)	18.1 (3.2)	5.67 (2.79)	70.9 (5.2)
	Low Bet	37.4 (3.7)	43.7 (4.1)	8.91 (4.45)	12.8 (3)
	No Bet	26.1 (4.7)	38.2 (5.1)	85.4 (5.7)	16.3 (3.5)

494 Notes: Brackets contain standard errors of the mean.

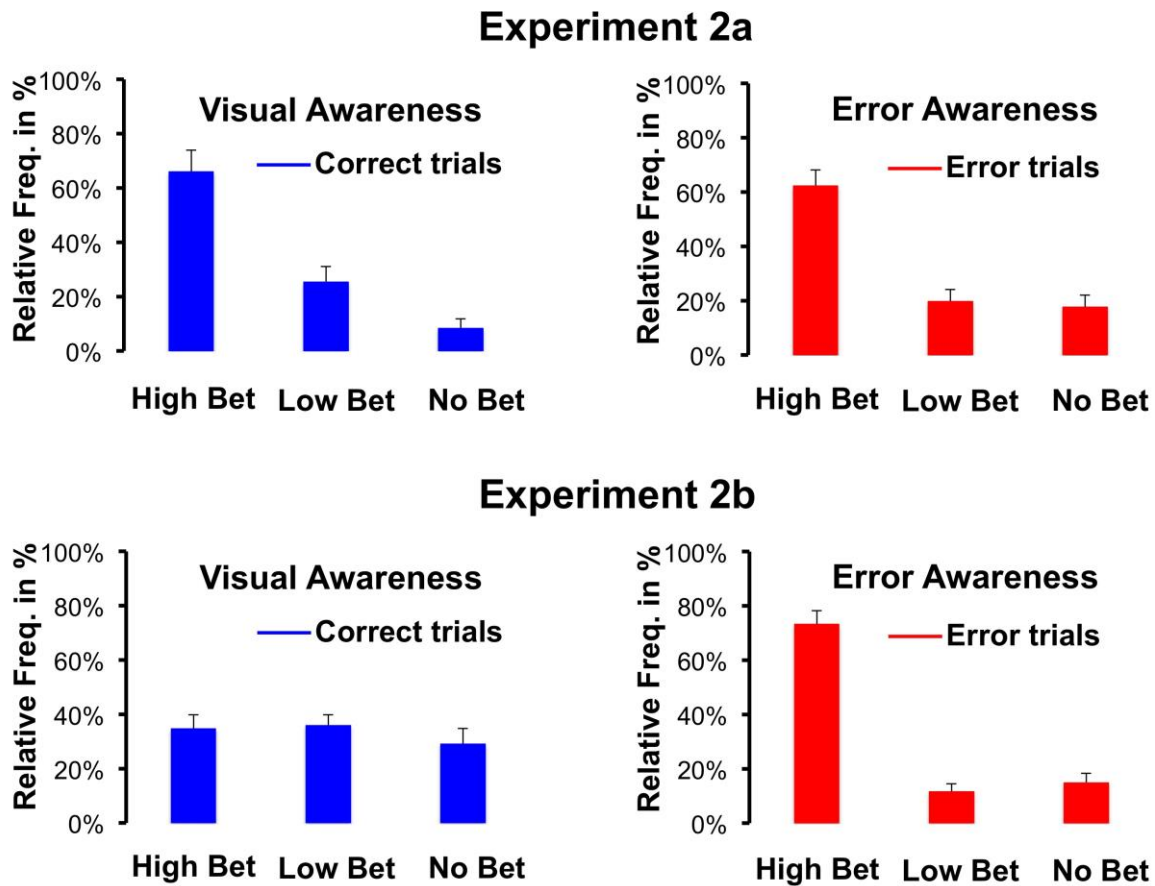
495

496 *Experiment 2a: Error Awareness Task.* In the Error Awareness task, we reduced errors  
 497 due to data limitation using a longer SMI but instead induced a high time pressure. The mean  
 498 error rate was 20.1% (SE = 2.5%), which corresponded to a mean number of errors of 172.8  
 499 (SE = 21.6). Participants were slower for correct trials (M = 296 ms, SE = 13 ms) than for  
 500 error trials (M = 234 ms, SE = 14 ms),  $t(19) = 7.33$ ,  $p < .001$ ,  $d = 1.82$ . Table 2 provides the  
 501 frequencies of secondary task responses among correct trials and error trials. Now,  
 502 participants had to bet on having experienced an early error sensation. As merely detecting an  
 503 error is rather easy in this task, it is not surprising that, on correct trials, the frequency of  
 504 correct/no bets (M = 85.3%; SE = 6.5%; 95%-CI = 82.1% - 88.2%) was much larger than the  
 505 frequencies of correct/low bets (M = 2.4%; SE = 0.9%; 95%-CI = 1.97% - 2.82%),  $t(19) =$   
 506 12.2,  $p < .001$ ,  $d = 2.75$ , and correct/high bets (M = 12.3%; SE = 6.3%; 95%-CI = 9.35% -

507 15.2%),  $t(19) = 5.71, p < .001, d = 1.28$ . Crucially, however, on error trials, the frequency of  
508 error/high bets ( $M = 62.4\%$ ;  $SE = 5.8\%$ ;  $95\%-CI = 59.7\% - 65.1\%$ ) was larger than the  
509 frequency of error/low bets ( $M = 19.8\%$ ;  $SE = 4.2\%$ ;  $95\%-CI = 17.8\% - 21.8\%$ ),  $t(19) = 4.72,$   
510  $p < .001, d = 1.05$ , and the frequency of error/no bets ( $M = 17.8\%$ ;  $SE = 4.7\%$ ;  $95\%-CI =$   
511  $15.6\% - 19.9\%$ ),  $t(19) = 4.58, p < .001, d = 1.03$  (see also Figure 3). This implies that  
512 participants were highly confident in experiencing early error detection on a large number of  
513 trials.

514 For analysis of primary task RTs, 3 participants who had no trial in one of the error  
515 conditions were excluded. However, the one-way ANOVA did not reveal any significant  
516 effects (error/high bets:  $M = 241$  ms,  $SE = 16$  ms; 113 trials;  $SE = 21.3$  trials; error/low bets:  
517  $M = 282$  ms,  $SE = 25$  ms; 33.9 trials;  $SE = 7.1$  trials; error/no bets:  $M = 361$  ms,  $SE = 61$  ms;  
518  $26.1$  trials;  $SE = 6.1$  trials),  $F(2,32) = 1.93, p = .18, \eta_p^2 = .11$ . When 7 further participants with  
519 fewer than 10 trials in one of the conditions were excluded, again no significant difference  
520 was revealed (error/high bets:  $M = 228$  ms,  $SE = 17$  ms; 122 trials;  $SE = 22.9$  trials; error/low  
521 bets:  $M = 250$  ms,  $SE = 26$  ms; 38.1 trials;  $SE = 7.3$  trials; error/no bets:  $M = 348$  ms,  $SE = 77$   
522 ms; 30.9 trials;  $SE = 6.2$  trials),  $F(2,22) = 1.59, p = .22, \eta_p^2 = .13$ .

523



524

525 *Figure 3: Results of Experiments 2a and 2b.* For the Visual Awareness task (left  
 526 column), the proportions of correct responses followed by high, low or no bets are reported  
 527 for Experiments 2a and 2b. For the Error Awareness task (right column), the proportions of  
 528 errors followed by high, low or no bets are reported for Experiments 2a and 2b. Error bars  
 529 represent standard errors of the mean.

530

531 *Experiment 2b: Visual Awareness Task.* The mean error rate in the Visual Awareness  
 532 task was 38.4% (SE = 2.3%), which corresponded to a mean number of errors of 165.9 (SE =  
 533 9.94). The RT difference between correct trials (M = 1176 ms, SE = 126 ms) and error trials  
 534 (M = 1264 ms, SE = 119 ms) was marginally significant,  $t(19) = 1.77, p = .093, d = 0.39$ .

535 Frequencies of secondary task responses are provided in Table 2. Notably, the reduced SMI in  
 536 Experiment 2b led to a drastic change of the pattern of wagering. On correct trials, neither the  
 537 difference between the frequencies of correct/high bets (M = 36.5%; SE = 5.1%; 95%-CI =  
 538 34.1% - 38.8%) and correct/low bets (M = 37.4.7%; SE = 3.7%; 95%-CI = 35.7% - 39.1%),  
 539  $t(19) = 0.12, p = .907, d = 0.03$  nor the difference between the frequencies of correct/low bets

540 and correct/no bets ( $M = 26.1\%$ ;  $SE = 4.8\%$ ;  $95\%-CI = 23.9\% - 28.3\%$ ) was significant,  $t(19)$   
541  $= 1.29$ ,  $p = .212$ ,  $d = 0.28$  (see also Figure 3). On error trials, the frequency of high bets ( $M =$   
542  $18.1\%$ ;  $SE = 3.3\%$ ;  $95\%-CI = 16.6\% - 19.6\%$ ) was significantly lower than the frequency of  
543 error/low bets ( $M = 43.7\%$ ;  $SE = 4\%$ ;  $95\%-CI = 41.8\% - 45.6\%$ ),  $t(19) = 4.61$ ,  $p < .001$ ,  $d =$   
544  $1.03$ , while the frequencies of error/low bets and error/no bets ( $M = 38.2\%$ ;  $SE = 5.1\%$ ;  $95\%-$   
545  $CI = 35.8\% - 40.6\%$ ) did not differ significantly,  $t(19) = 0.55$ ,  $p = .589$ ,  $d = 0.12$ . These data  
546 show that the small SMI led to considerable response uncertainty in this task.

547 *Experiment 2b: Error Awareness Task.* The mean error rate was  $19.1\%$  ( $SE = 1.9\%$ ),  
548 which corresponded to a mean number of errors of  $165$  ( $SE = 17.28$ ). Participants were slower  
549 on correct trials ( $M = 331$  ms,  $SE = 10$  ms) than on error trials ( $M = 275$  ms,  $SE = 15$  ms),  
550  $t(19) = 5.09$ ,  $p < .001$ ,  $d = 1.13$ . Table 2 provides the frequencies of secondary task responses.  
551 Among correct trials, the frequency of correct/no bets ( $M = 85.4\%$ ;  $SE = 5.7\%$ ;  $95\%-CI =$   
552  $82.7\% - 88.1\%$ ) was again larger than the frequencies of correct/low bets ( $M = 8.91\%$ ;  $SE =$   
553  $4.45\%$ ;  $95\%-CI = 6.8\% - 10.9\%$ ),  $t(19) = 7.76$ ,  $p < .001$ ,  $d = 1.73$ , and correct/high bets ( $M =$   
554  $5.67\%$ ;  $SE = 2.79\%$ ;  $95\%-CI = 4.4\% - 6.97\%$ ),  $t(19) = 10.2$ ,  $p < .001$ ,  $d = 2.28$ . On error  
555 trials, the frequency of error/high bets ( $M = 70.9\%$ ;  $SE = 5.2\%$ ;  $95\%-CI = 68.5\% - 73.3\%$ )  
556 was larger than the frequency of error/low bets ( $M = 12.8\%$ ;  $SE = 3\%$ ;  $95\%-CI = 11.5\% -$   
557  $14.3\%$ ),  $t(19) = 7.53$ ,  $p < .001$ ,  $d = 1.68$ , and the frequency of error/no bets ( $M = 16.3\%$ ;  $SE =$   
558  $3.5\%$ ;  $95\%-CI = 14.7\% - 17.9\%$ ),  $t(19) = 6.55$ ,  $p < .001$ ,  $d = 1.47$  (see also Figure 3). This  
559 again suggests that participants rather consistently experienced early error detection in this  
560 task.

561 The one-way ANOVA on the primary task RTs did not reveal any significant effect  
562 (error/high bets:  $M = 271$  ms,  $SE = 21$  ms; 115 trials;  $SE = 14.9$  trials; error/low bets:  $M =$   
563  $437$  ms,  $SE = 130$  ms; 18.8 trials;  $SE = 5.5$  trials; error/no bets:  $M = 347$  ms,  $SE = 44$  ms; 24.8  
564 trials;  $SE = 4.9$  trials;),  $F(2,38) = 2.73$ ,  $p = .11$ ,  $\eta_p^2 = .13$ . When 9 participants were excluded

565 that had fewer than 10 trials in one of the conditions, again no significant difference was  
566 obtained (error/high bets:  $M = 283$  ms,  $SE = 23$  ms; 108 trials;  $SE = 14.7$  trials; error/low  
567 bets:  $M = 301$  ms,  $SE = 22$  ms; 31.6 trials;  $SE = 6.1$  trials; error/no bets:  $M = 303$  ms,  $SE = 23$   
568 ms; 32.8 trials;  $SE = 5.9$  trials),  $F(2,20) = 0.51$ ,  $p = .61$ ,  $\eta_p^2 = .05$ .

569 *Comparison across tasks and Experiments 2a and 2b.* In a further analysis, we  
570 compared the frequencies of high bets in the Visual Awareness task and Error Awareness task  
571 across Experiments 2a and 2b to investigate whether the reference point set in the Visual  
572 Awareness task influenced wagering in the Error Awareness task. To this end, we included  
573 data from correct trials in the Visual Awareness task (because participants placed bets on  
574 being correct) and from errors in the Error Awareness task (because participants placed bets  
575 on experiencing early error detection) in the analysis, as summarized in Figure 3. The  
576 resulting mixed-model ANOVA with the within-participants variable task (Visual Awareness,  
577 Error Awareness) and the between-participants variable experiment (Exp. 2a, Exp. 2b)  
578 revealed a significant main effect of task,  $F(1,38) = 7.79$   $p = .008$ ,  $\eta_p^2 = .173$ , and a significant  
579 interaction between both variables,  $F(1,38) = 9.31$   $p = .004$ ,  $\eta_p^2 = .197$ . Independent samples  
580 t-tests showed that, in the Visual Awareness task, the frequency of high bets was larger for  
581 correct trials in Experiment 2a than in Experiment 2b,  $t(38) = 3.39$ ,  $p = .002$ ,  $d = 0.76$ , thus  
582 reflecting the increased difficulty of the Visual Awareness task in Experiment 2b. In contrast,  
583 in the Error Awareness task, the frequency of high bets on errors did not differ between  
584 experiments,  $t(38) = 1.09$ ,  $p = .282$ ,  $d = 0.21$ , suggesting that the different reference points in  
585 the Visual Awareness task did not influence wagering in the Error Awareness task. Indeed,  
586 the frequency of high bets across tasks differed significantly only in Experiment 2b,  $t(19) =$   
587  $4.26$ ,  $p < .001$ ,  $d = 0.95$ , but not in Experiment 2a,  $t(19) = 0.39$ ,  $p = .71$ ,  $d = 0.09$ .

588 *Early error detection across Experiments 1 and 2.* In a final analysis step, we  
589 compared the frequencies of early error sensations across Experiment 1 and 2 to investigate

590 whether early detected errors occur similarly across experimental methods. We assume that  
591 error/high bet trials from Experiment 2 correspond to trials with truly experienced early error  
592 sensations. As Experiment 1a presumably overestimated the rate of early error sensations  
593 because classified early errors also included guesses, we compared the rate of early error  
594 sensations among errors from Experiment 1b with the rates of high bet trials among errors  
595 from Experiments 2a and 2b. The one-way ANOVA between groups on the frequency of  
596 early detected errors showed no significant difference,  $F(2,57) = 2.02$   $p = .142$ ,  $\eta_p^2 = .033$ .  
597 Moreover, we directly compared the two methodological approaches contrasting participants'  
598 rates of early error sensations in Experiment 1b (20 participants) and 2a/2b (40 participants).  
599 The result of the independent samples t-test also showed no significant difference,  $t(58) =$   
600  $1.35$ ,  $p = .18$ ,  $d = 0.17$ . The estimated mean of early detected errors across the two  
601 experimental methods was 63.5% (SE = 3.71).

602

### 603 *Discussion*

604 Experiment 2 employed post-decision wagering to measure the confidence associated  
605 with reports of early error sensations. Moreover, a Visual Awareness task was used to provide  
606 a reference point that should guide participants' wagering on early error sensations. They  
607 were instructed to place high bets on early error sensations only if their confidence was  
608 comparable to high bets in the Visual Awareness task. The results indicate that, averaged  
609 across Experiments 2a and 2b, participants perceived early error detection with high  
610 confidence on about 67% of trials. Impressively, this is very similar to (and does not differ  
611 significantly from) the rate of early detected errors in Experiment 1b (59%).

612 A further goal of this experiment was to investigate whether reports on early error  
613 detection are influenced by an expectation bias. To this end, the Error Awareness task was  
614 preceded by either a less (Exp. 2a) or more (Exp. 2b) difficult Visual Awareness task.

615 Manipulating the difficulty of this task successfully led to strong shift in wagering. Whereas  
616 66% of correct responses led to a high bet in Experiment 2a, only 37% of correct responses  
617 led to a high bet in Experiment 2b. However, wagering in the Error Awareness task was fully  
618 independent of this manipulation. This clearly shows that expectations about how many high  
619 bets might be expected based on the Visual Awareness task had no effect at all on wagering in  
620 the Error Awareness task.

### 621 **General Discussion**

622 Participants in experiments on error detection frequently report that they already knew  
623 that an error has occurred before the response was executed, a phenomenon we term early  
624 error sensation. The goal of the present study was to investigate whether these anecdotally  
625 reported early error sensations exist and whether they can be reliably reported. In four  
626 experiments using two experimental approaches, we provided evidence that early error  
627 sensations indeed exist, and that they occur on the majority of error trials. When participants  
628 were asked to classify responses in a flanker task either as being correct, as early detected  
629 errors, or as late detected errors in Experiment 1a, they reported early errors in 73.7% of  
630 errors. When an additional category for detected errors with unclear timing was introduced in  
631 Experiment 1b, early errors were reported in 59.1% of trials. When participants had to wager  
632 on the feeling of early error detection, they placed high bets on 62.4% (Exp. 2a) and 70.9%  
633 (Exp. 2b). These data demonstrate that early error sensations are reported very consistently  
634 across different primary tasks (flanker task vs. number/let discrimination) and secondary tasks  
635 (error classification vs. post-decision wagering).

636 Crucial, however, is the question whether these introspective reports indeed reflect  
637 that errors were detected before the response, or whether participants were unable to  
638 discriminate between early and late errors and simply guessed that early errors must  
639 occasionally occur. A challenging problem for measuring early error sensations is that we



640 cannot objectively determine whether a given error was detected early or late. To deal with  
641 this problem, we introduced a reference for the metacognitive reports of early error  
642 sensations. In Experiment 2, we used a Visual Awareness task in which participants had to  
643 wager on the accuracy of their responses. In the subsequent Error Awareness task, we  
644 instructed participants to place high bets on early error sensations only if they were similarly  
645 confident as for the high bets in the Visual Awareness task. We argued that this induces a  
646 common metric for judging confidence of the two tasks, which allowed us to interpret the  
647 metacognitive reports of early error detection with respect to the metacognitive judgments of  
648 visual awareness. This reasoning receives support from previous findings showing that  
649 humans represent confidence in a task-unspecific format which allows them to compare  
650 confidence across tasks with a similarly high precision as confidence within tasks (de  
651 Gardelle & Mamassian, 2014). Moreover, it has recently been suggested that integrating  
652 information from different sources into a common metric might even be the major purpose of  
653 metacognition (Shea & Frith, 2019). In Experiment 2a, the frequencies of high bets were  
654 coincidentally similar in both tasks. We can thus infer that the average confidence by which  
655 participants reported early error sensations in this experiment corresponded to the average  
656 confidence by which they were aware of the visual stimuli in the Visual Awareness task. This  
657 confidence level ought to be rather high given that the objective performance in the Visual  
658 Awareness task was far above chance level.

659         We found no evidence that metacognitive reports of early error sensations were  
660 subject to an expectation bias. If participants simply guessed that early error sensations must  
661 occasionally occur, these guesses should be influenced by expectations about the frequency of  
662 early error sensations. To investigate whether such an expectation bias exists, we manipulated  
663 the difficulty of the Visual Awareness task, and thus the frequency of high bets in this task.  
664 However, whereas the frequency of high bets in the Visual Awareness task varied between

665 Experiments 2a and 2b, the frequency of high bets in the Error Awareness task remained  
666 constant across the two experiments. This suggests that metacognitive judgments about early  
667 error sensations are not influenced by a specific expectation bias induced by the frequency of  
668 high bets in the Visual Awareness task. While we cannot fully exclude a general bias towards  
669 instruction-driven expectations about early error sensations, our results strongly suggest that  
670 metacognitive judgments on early error sensations are very consistent and reliable across  
671 experimental procedures.

672         We found no evidence that early and late detected errors differ with respect to any  
673 objective features. It has been reported that uncertainty or conflict during response selection  
674 can influence post-response decision process and metacognitive judgments about errors  
675 (Steinhauser et al., 2008; Yeung & Summerfield, 2012). As a consequence, variables like  
676 stimulus congruency or RT could potentially influence subjective judgments about early error  
677 sensations. However, we found no robust evidence that this was the case in the present study.  
678 Participants reported early error sensations in a similar proportion for congruent and  
679 incongruent errors in Experiment 1. Moreover, RTs were similar across all error types. A  
680 small RT difference between early and late detected errors in Experiment 1a disappeared  
681 when we controlled for errors with unclear timing in Experiment 1b. This suggests that the  
682 emergence of early error sensations is not related to specific features of task processing like  
683 stimulus congruency or RTs. Thus, our data provide little evidence that early error sensations  
684 reflect the objective latency of error detection, which has been found to correlate with RT  
685 when response speed was directly manipulated (Steinhauser et al., 2008).

686         An important question is why early error sensations occurred on the majority of trials  
687 whereas the neural correlates of error awareness emerge not until 300 ms after an error (e.g.,  
688 Steinhauser & Yeung, 2010). There are at least two possible explanations. A first explanation  
689 is that conclusions about the timing of error awareness from EEG measures like the Pe are

690 incorrect. The Pe is often considered the earliest neural correlate of error awareness and the  
691 role of the Pe for the emergence of error awareness has been described within an evidence  
692 accumulation account (Steinhauser & Yeung, 2010; Ullsperger, Harsay, Wessel, &  
693 Ridderinkhof, 2010). It is assumed that the Pe reflects the accumulated evidence that an error  
694 has occurred, and that error awareness emerges when this evidence exceeds a threshold. The  
695 evidence is provided by cognitive, autonomous, motor and sensory processing (Bode & Stahl,  
696 2014; Wessel, Danielmeier, Morton, & Ullsperger, 2012; Wessel, Danielmeier, & Ullsperger,  
697 2011), but does not necessarily rely on early error processing represented by the Ne/ERN (Di  
698 Gregorio, Maier, & Steinhauser, 2018). One possibility is that the feeling of error awareness  
699 emerges already before the Pe, for instance, at the time point of the Ne/ERN or even earlier  
700 (Bode & Stahl, 2014). The Pe could represent a later stage of metacognitive processing,  
701 perhaps related to the emergence of confidence about response accuracy (Boldt & Yeung,  
702 2015).

703         A second explanation is that early error sensations are a metacognitive illusion. Error  
704 awareness could emerge at the time of the Pe but the illusion is created that the error has been  
705 detected already before the response. This mechanism could serve to subjectively synchronize  
706 error awareness with the timing of the objective error in the same way as visual awareness is  
707 subjectively aligned with the onset of a visual stimulus. In the context of visual awareness,  
708 expectations and other top-down variables can influence the accumulation of sensory  
709 evidence and consequentially metacognitive judgments about stimulus awareness (de Lange,  
710 Jensen, & Dehaene, 2010; Kouider, de Gardelle, Sackur, & Dupoux, 2010) . Moreover, a  
711 backward referral process has been assumed to synchronize the subjective time point of visual  
712 awareness with the objective stimulus to create a coherent perception in the stream of  
713 consciousness (Libet et al., 1979, 1983). A similar process could align the subjective time  
714 point of error awareness with the emergence of the objective error. This temporal alignment

715 of actions (i.e., a response) and their effects (i.e., the feeling of being incorrect) could further  
716 serve to evoke a sense of agency, i.e., the feeling of having caused an effect. Indeed, previous  
717 studies have shown that action-effect contingencies are influenced by their temporal  
718 contiguity and vice versa. Humans tend to perceive two events more causally related the  
719 closer they occur in time (Greville & Buehner, 2010), and causality judgments correlate with  
720 the perceived temporal contiguity between actions and their sensory effects (Haering &  
721 Kiesel, 2016). In other words, these metacognitive illusions on early error sensations could  
722 serve to reconstruct temporal contiguity between perception, action and metacognitive  
723 contents (Kouider, de Gardelle, Sackur, & Dupoux, 2010).

724         While we obtained clear and robust results across several experiments, the present  
725 method has also some limitations. A first limitation is that using a categorical measure for the  
726 timing of error detection implies a loss of information as time is a continuous phenomenon.  
727 However, differentiating only between errors detected before and after the response has the  
728 advantage of imposing considerably lower cognitive load than using a continuous measure.  
729 For instance, in the classical Libet studies (Libet et al., 1983), participants had to indicate the  
730 time of voluntary action initiation on a visual clock. However, in addition to considerable  
731 methodological weaknesses (Trevena & Miller, 2002), monitoring a clock represents a  
732 difficult secondary task that presumably interferes with both, the primary task and the task to  
733 detect errors. In contrast, our categorical measure uses the response as a reference rather than  
734 a continuous timer. As error detection already involves response monitoring (Steinhauser et  
735 al., 2008), only minimal additional load should be imposed.

736         As already discussed, a second limitation is that we have no objective measure that  
737 verifies the existence of early error sensations. Future studies could solve this problem by  
738 measuring neural correlates of early error sensations. Strong evidence for the existence of  
739 early error sensations would be provided if not only the Pe but also the earlier Ne/ERN would

740 correlate with early error sensations. If only the Pe differed between early and late detected  
741 errors, this would suggest that early error sensations emerge during the later stage of  
742 conscious error processing. However, if such a difference was found also for the Ne/ERN, this  
743 would point to early error signals such as response conflict (Yeung et al., 2004) or prediction  
744 errors (Holroyd & Coles, 2002) as the origin of early error sensations. It is even possible that  
745 brain activity preceding the response can affect metacognitive judgments on early error  
746 sensations. ERP differences between errors and correct responses have been found prior to the  
747 response (Bode & Stahl, 2014) or even on the previous trial of simple tasks (Hajcak,  
748 Nieuwenhuis, Ridderinkhof, & Simons, 2005; Hoonakker, Doignon-Camus, & Bonnefond,  
749 2016; Ridderinkhof, Nieuwenhuis, & Bashore, 2003), as well as in tasks involving complex  
750 sequences of motor programs such as piano playing (Maidhof, Rieger, Prinz, & Koelsch,  
751 2009). In a similar vein, a study using self-report measures has revealed that internal error  
752 prediction occurs before responses in skilled typing (Rieger & Bart, 2016). Here, the question  
753 arises whether this activity serves as a cue for metacognitive judgments, or whether  
754 metacognition relies on direct access to the timing of these neural events.

755         A further question is whether early error sensations are related to early incorrect  
756 response activation. On correct trials, early incorrect response activation leads to a  
757 phenomenon called partial errors (Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002;  
758 Coles, Scheffers, & Fournier, 1995; Endrass, Klawohn, Schuster, & Kathmann, 2008), which  
759 can be consciously reported by participants (Rochet, Spieser, Casini, Hasbroucq, & Burle,  
760 2014). Future studies could investigate whether such early incorrect response activation on  
761 error trials is responsible for early error sensations. Indeed, lower response force for errors  
762 than correct responses has been shown in skilled typing (Rabbitt, 1978). As this phenomenon  
763 has been interpreted as resulting from inhibition of the error response before actual response  
764 execution, it could be taken as indirect evidence for early error sensations. Future studies

765 could examine whether errors accompanied by early error sensations are executed with lower  
766 response force than late errors.

767         The present study provides first evidence that participants have the subjective feeling  
768 of detecting errors already before they occurred. We show that these early error sensations can  
769 be robustly measured across different tasks and metacognitive judgments. Our results add to  
770 the broad body of evidence that humans have metacognitive access to a multitude of  
771 performance parameters. Previous studies could show that participants are able to report  
772 whether an error has occurred or not (Rabbitt, 1968, 2002), to provide graded confidence  
773 judgments on the accuracy of their response (Boldt & Yeung, 2015), to classify the type of  
774 error they committed (i.e., to which distractor stimulus they responded; Di Gregorio,  
775 Steinhauser, & Maier, 2016), and to estimate their RTs in choice tasks (Bryce & Bratzke,  
776 2014). These metacognitive contents are used for optimizing decision processes (Desender,  
777 Boldt, & Yeung, 2018; Desender, Van Opstal, & Van den Bussche, 2014). Metacognitive  
778 representations on the timing of error detection could form another piece of information to  
779 support this optimization.

780

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783

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