1 **Relationships between individual differences in dual process and electrophysiological**

2 **signatures of familiarity and recollection during retrieval**

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15 **Abstract**

16 Our everyday memories can vary in terms of accuracy and phenomenology. According to one

17 theoretical account, these differences hinge on whether the memories contain information

18 about both an item itself as well as associated details (remember) versus those that are devoid

19 of these associated contextual details (familiar). This distinction has been supported by

20 computational modeling of behavior, studies in patients, and neuroimaging work including

21 differences both in electrophysiological and functional magnetic resonance imaging. At

22 present, however, little evidence has emerged to suggest that neurophysiological measures

23 track individual differences in estimates of recollection and familiarity. Here, we conducted

24 electrophysiological recordings of brain activity during a recognition memory task designed

25 to differentiate between behavioral indices of recollection and familiarity. Non-parametric

26 cluster-based permutation analyses revealed associations between electrophysiological

27 signatures of familiarity and recollection with their respective behavioral estimates. These

28 results support the idea that recollection and familiarity are distinct phenomena and is the

29 first, to our knowledge, to identify distinct electrophysiological signatures that track

30 individual differences in these processes.

31 **Introduction**

32   We have all had the experience of running into someone we know walking down the

33   street. Sometimes just seeing that person can help us recollect their name and where and when

34   we last encountered them. At other times, we might feel confident that we have met that

35   person because the face seems so familiar, even if we are otherwise unable to recover any

36   details about that person. A long history of memory research has suggested that recollection

37   and familiarity vary in terms of retrieved information (i.e., item vs. context information),

38   vividness (Cooper and Ritchey, 2019; Jacoby and Dallas, 1981; Roediger and Blaxton, 1987;

39   Tulving, 2002; Woroch and Gonsalves, 2010), and subjective experience (Leynes and

40   Nagovsky, 2016; Souchay et al., 2013). Moreover, studies using electroencephalography

41   (EEG; Addante et al., 2012b; Curran, 2002; Diana et al., 2011; Duarte et al., 2004; Düzel et

42   al., 1997; Leynes and Phillips, 2008; Rugg and Curran, 2007; Tsivilis et al., 2001; Wilding et

43   al., 1995; Woroch and Gonsalves, 2010), magnetoencephalographic (Evans and Wilding,

44   2012), studies of patients with brain damage (Addante et al., 2012a; Aggleton et al., 2005;

45   Aly et al., 2011; Bowles et al., 2010; Duarte et al., 2005, 2004; Wang et al., 2014, 2014), and

46   functional magnetic resonance imaging (fMRI; Diana et al., 2012, 2007; Eldridge et al., 2000;

47   Vilberg et al., 2006; Vilberg and Rugg, 2008; Yonelinas et al., 2005) are consistent with the

48   idea that recollection and familiarity depend on different neural substrates. Accordingly, many

49   theories (Jacoby, 1991; Mandler, 1980; Tulving, 1985; Yonelinas, 1999) and computational

50   models (Elfman et al., 2014; Norman and O'Reilly, 2003; Selmeczy and Dobbins, 2014) have

51   proposed that recollection and familiarity are driven by different processes (see Eichenbaum

52   et al., 2007; Ranganath, 2010a, 2010b; Ranganath and Rainer, 2003; Reagh and Ranganath,

53   2018; Wilding and Ranganath, 2012; Yonelinas, 2002 for extensive reviews of this literature),

54   though this idea remains somewhat controversial (e.g., Wixted, 2007).

55   One class of models (Park and Donaldson, 2019; Yonelinas, 2002, 1999, 1994;

56   Yonelinas et al., 2010) particularly emphasizes the idea that recollection and familiarity can

57   be distinguished on the type of associated details recovered, as well as phenomenology.

58   According to this view, familiarity is typically associated with strong memory for an item

59   with minimal information about associated contextual details, whereas recollection is

60   accompanied by retrieval of information about the item and about the context in which it was

61   encountered (Addante et al., 2012a; Diana et al., 2008; Eichenbaum et al., 2007; Ranganath,

62   2010b; Yonelinas, 2002, 1999, 1994; Yonelinas et al., 2010).

63   Many studies have used recordings of event-related potentials (ERPs) to differentiate

64   between neural correlates of recollection and familiarity based on sensitivity to particular

65   experimental variables, temporal dynamics, and scalp topography (Addante et al., 2012b;

66   Bridger et al., 2012; Curran, 2004, 2000; Park and Donaldson, 2019; Rugg et al., 1998a,

67   1998b; Rugg and Curran, 2007; Wilding and Herron, 2006, 2006; Wilding and Ranganath,

68   2012), but there is significant controversy over how these results should be interpreted (Hou

69   et al., 2013; Lucas et al., 2010; Nie et al., 2014; Paller et al., 2007; Thakral et al., 2016; Voss

70   et al., 2012; Voss and Paller, 2016, 2006; Yovel and Paller, 2004). Many studies have

71   reported ERP differences between old and new items (i.e., an ERP "old-new effect") around

72   300-600 ms post-stimulus, with a mid-frontal or fronto-central scalp topography (Curran et

73   al., 2006; Friedman and Johnson, 2000; Mecklinger, 2006, 2000; Rhodes and Donaldson,

74   2007; Tsivilis et al., 2001). The topography and latency of this "mid-frontal old-new

75   effect"(Rugg et al., 1998a) resembles the N400 ERP component reported in psycholinguistic

76   studies (Kutas and Hillyard, 1984), although the mid-frontal old-new effect often has a more

77   anterior distribution (Wilding and Ranganath, 2012). The mid-frontal old-new effect has often

78   been contrasted with a late-onsetting old-new effect that is maximal at parietal sites. This

79   latter effect has been called the "parietal old-new effect" or the late positive component (LPC)

80   (Friedman and Johnson, 2000; Olichney et al., 2000; Paller and Kutas, 1992; Smith, 1993;

81   Wilding and Ranganath, 2012), and is more left-lateralized for words and more widespread

82   for pictures and actions (Leynes et al., 2017).

83   Results from a number of studies have been used to support the idea that the mid-

84   frontal old-new effect may be a neural correlate of familiarity, whereas the parietal old-new

85   effect may be a neural correlate of recollection (Addante et al., 2012b; Friedman and Johnson,

86   2000; Griffin et al., 2013, 2013; Leynes et al., 2005; Olichney et al., 2000; Paller and Kutas,

87   1992; Park and Donaldson, 2019; Rhodes and Donaldson, 2007; Rugg et al., 1998b; Speer

88   and Curran, 2007; Wilding and Ranganath, 2012, 2012; Wynn et al., 2020, 2020) for reviews

89   see (Curran et al., 2006; Friedman, 2013; Friedman and Johnson, 2000; Rugg and Curran,

90   2007), although results from other studies have argued against this idea (Bridger et al., 2012;

91   Greve et al., 2007; Kelley and Wixted, 2001; Leynes et al., 2017; Paller et al., 2007; Voss and

92   Federmeier, 2011; Voss and Paller, 2006; Yovel and Paller, 2004). One complication in

93   interpreting studies differentiating between the mid-frontal and parietal old-new effects is that

94   the exact timing and topography of these effects can differ considerably across studies, and it

95   is possible that recollection and familiarity might be differentiated by ERP modulations that

96   do not exhibit the typical characteristics of these two old-new effects (Friedman et al., 2005;

97   Ranganath and Paller, 2000; Tsivilis et al., 2001). Data-driven ERP analysis methods (Maris

98   and Oostenveld, 2007) might offer a way to reconcile these views and identify the extent to

99   which recollection and familiarity can be differentiated.

100   It is also notable that most ERP studies have focused on old-new effects in group

101   averages, and little is known about whether ERP modulations track individual differences in

102   memory performance. If different ERP measures are predictive of putatively different

103   memory processes, there should be unique correlations between the behavioral and ERP

104   measures of each memory process. Recently, several studies have focused on correlating

105   ERPs with individual differences in recognition memory performance (Amico et al., 2015;

106   Angel et al., 2010; Chen et al., 2014; MacLeod and Donaldson, 2017), but these studies have

107   not revealed a clear picture. Angel et al. (2010) correlated overall recognition memory

108   performance (corrected recognition rate) with the magnitude of the parietal old-new effect,

109   but this study was performed on a small sample (14 participants), and it focused only on the

110   parietal old-new effect within an a priori time widow. More recently, MacLeod and

111   Donaldson (2017) correlated the magnitude of the left parietal old-new effect with recognition

112   performance. Across three tasks, the authors found significant old/new effects in the left

113   parietal ERP (Hit>CR; R-CR > K-CR), but correlations between the ERP and behavioral

114   measures were inconclusive. This may have arisen because, although the total number of

115   participants was high (122), only 20 participants were included in the correlation of R/K

116   effect magnitude with behavioral data. In addition, these analyses focused only on the late left

117   parietal effect, estimated as the mean ERP difference within an a priori time widow, averaged

118   across three parietal electrodes and did not attempt to differentiate correlates of recollection-

119   and familiarity-based recognition. Chen et al. (2014) correlated FN400 (mid-frontal old-new

120   effect) magnitudes with recognition performance in a large sample (64 participants), but this

121   study used only overall recognition discriminability (d′) and response time as behavioral

122   indices of memory performance, which does not distinguish recollection from familiarity.

123   Whereas the above studies focused specifically on previously identified ERP old-new effects,

124   Amico et al. (2015) used data-driven non-parametric analyses to characterize individual

125   differences in overall recognition performance (Hit and FA rates, the sensitivity index d', the

126   decision criterion c, and the mean RT for Hit trials). However, this study had a relatively

127   small sample size (18 participants) and did not attempt to separately estimate familiarity and

128   recollection.

129   To summarize, prior studies have focused on relationships between ERP components

130   and recognition memory performance, but no previous study, to our knowledge, has shown a

131   relationship between individual differences in behavioral estimates of recollection and

132   familiarity and the putative ERP correlates of these processes described above. Furthermore,

133   given the known variability in timing and topography in these EEG signatures with different

134   types of stimuli, there is no agreed upon standard definition that can be applied consistently

135   across studies.

136   The present study seeks to address these limitations by testing the hypothesis that

137   individual differences in recognition memory performance are related to variability in

138   electrophysiology in terms of two recognition memory processes: familiarity and recollection.

139   In order to test whether individual differences in electrophysiological signatures of familiarity

140   and recollection were related to differences in their dual process estimates, we measured

141   ERPs while participants made recognition memory judgments using the Remember/Know

142   method (Tulving, 1985). To identify ERPs related to individual differences in familiarity and

143   recollection in an unbiased manner, we used a data-driven analysis approach in which ERP

144   differences were correlated with individual differences in dual process estimates of familiarity

145   and recollection using non-parametric cluster-based permutation analysis. If dual process

146   estimates of familiarity and recollection are associated with particular electrophysiological

147   signatures, we should observe correlations between familiarity-related ERPs and familiarity

148   dual process estimates and between recollection-related ERPs and recollection dual process

149   estimates.

150

151   **Methods**

152   *Participants*

153   49 participants took part in the study. They were right-handed and had normal or

154   corrected-to-normal visual acuity and no history of neurological or psychological disorders.

155   Participants were excluded due to contamination of mastoid channels (N=1), incidental MRI

156   finding (N=1), not completing the task (N=2), and not fulfilling the inclusion criteria of at

157   least 30 recollection trials (Boudewyn et al., 2018; Cohen, 2014; Luck, 2014, 2005), N=7).

158   Thus, 38 participants (N_{female} = 26, mean age = 25.7±4.2 years) were included in the final

159   analyses. A post-hoc sensitivity analysis of a bivariate normal model correlation using

160   G*Power 3.1 software (Faul et al., 2009, 2007) with a two tailed alpha value of 0.05 showed

161   that a sample size of 38 with a power of 0.8 could detect a medium to large effect size of

162   0.436 (Cohen, 1988) with a correlation interval of ±0.32. The study was approved by the

163   Institutional Review Board of the University of California at Davis and all participants

164   provided informed consent prior to participation. Participants were compensated $20/hr for

165   their time.

166

167　　*Stimuli*

168　　　　　Study materials came from the Bank of Standardized Stimuli (BOSS) developed by

169　　Brodeur and colleagues (Brodeur et al., 2014, 2010). Using the normative data provided by

170　　the BOSS creators, we selected the images that were well-agreed on for the name (>29%),

171　　category (>29%), object (>2 on a 1-5 scale), and viewpoint (>2 on a 1-5 scale), and rated as

172　　familiar (>2 on a 1-5 scale), and simple (<2 on a 1-5 scale for complexity). Duplicate items

173　　were removed as well as items in any of the animal ("Crustacean", "Mammal", "Reptile",

174　　"Bird", "Insect", "Canine", "Feline", "Sea mammal", "Fish"), body part, and war weapon

175　　categories. In addition, any potentially emotional, disturbing, or unpleasant images were

176　　removed (e.g., syringe, hunting knife) as well as objects that a research assistant deemed hard

177　　to recognize (e.g., contact lens) or redundant with another object. Images were re-sized in

178　　Adobe Photoshop to 500 x 500 pixels. Objects from this list of 644 remaining objects were

179　　then used to generate study and lure lists. Object categories used in the stimuli represent the

180　　general makeup of the original BOSS stimuli (see Brodeur et al., 2014, 2010 for details).

181　　Original stimuli used in the paradigm (https://osf.io/4s7uy/) as well as the original source

182　　code for stimulus presentation

183　　(https://github.com/hallez/eetemp_eeg_pub/tree/main/experiment-scripts) are available online.

184　　　　　270 objects were uniquely drawn for each subject such that each participant saw a

185　　distinct set of items although, by chance, some objects necessarily overlapped between

186　　participants. Of the 270 objects selected for a participant, 180 images were used as study

187　　items during the encoding phase and 90 were used as lures during the retrieval phase. 180

188　　study items were divided into five encoding lists of 36 items each. One of four encoding

189　　questions ("Would you find this item in a supermarket/convenience store?", "Would this item

190　　fit in a fridge/bathtub?") was paired with each item. In each of the five encoding lists, each

191　　question was paired with 9 different items such that each question was used the same number

192　　of times in each encoding list. Lists for object retrieval were constructed by randomly

193　　selecting 30 studied and 15 lure items. The proportion of objects from each encoding list (1-5)

194　　and encoding question (fridge/bathtub/supermarket/convenience store) was not constrained in

195　　the construction of the retrieval lists. This manipulation was used to ensure the participants

196　　were paying attention to individual items and was not included in the analyses described in

197　　this work. For a retrieval list, the 180 studied items and 90 lure items were randomly

198　　intermixed, using the *numpy.random.shuffle* tool in Python (Version 2.7.14). Participants

199　　were given a practice phase with four objects. Objects used in the practice phase were drawn

200　　from a separate stimulus set of computer-generated images (previously used in (Dimsdale-

201 Zucker et al., 2018) so that they would not be confused with any of the studied items. Four

202 practice objects were randomly selected for each subject from a set of 12 objects.

203

Procedure

205   The experiment comprised of practice, encoding, and retrieval phases. EEG data were

206 collected during the retrieval phase. Each trial during the retrieval phase included object

207 recognition and source memory test components. The present study focuses on the EEG

208 signature that differentiates recollection and familiarity during item recognition as measured

209 with respect to the object recognition judgment.

210   For practice, a research assistant walked the participant through each phase of the task.

211 The practice for encoding was followed by familiarizing participants with the response scales

212 that were used for the object recognition and source judgments. Participants were told that the

213 difference between familiarity and recollection is that familiarity is feeling like they know or

214 have seen this item but being unable to recall from where. In contrast, recollection is

215 accompanied by memory for both the item itself as well associated details (e.g. an experience

216 or association from when the item was originally studied, the source or context of the item).

217 This description was supplemented with an example of meeting someone in the grocery store

218 and either feeling like you know them but not having access to their name or how you know

219 them ("familiar") versus running into an individual and knowing their name or where you've

220 encountered them previously ("remember"). New responses were explained as being

221 analogous to the experience of meeting a stranger or a totally novel person. The participants

222 were given practice trials along with feedback from the experimenter and detailed instructions

223 to ensure they understood how to use this response scale.

224   During the encoding phase, objects and questions ("Would this item fit in a fridge?",

225 etc.) appeared on the screen for 250 ms. Within each list, all four questions were presented in

226 a random order, an equal number of times across items. The participant made their response to

227 the question during this interval. A short presentation time was used in order to eliminate

228 potential eye movements during encoding. Response key mappings for the yes/no judgments

229 were randomized across participants. Responses were recorded but accuracy was not analyzed

230 as the purpose of this task was simply to orient participants to the objects and their respective

231 sources. Between lists, there was a 30 second break before the text label (e.g. "List 1") for the

232 next list was shown.

233   After studying all 180 objects, participants were then setup for EEG recording. Details

234 of the EEG setup can be found in the *EEG acquisition and processing* section. This cap setup

235 served as the delay period (approximately 45-60 min) between the encoding and retrieval

236 phases. During the retrieval phase, participants saw 270 objects (180 old and 90 novel) split

237 across six blocks of 45 trials (30 old and 15 novel objects). Each block began with a 23

238 second warm up period that walked the subject through getting in a comfortable position,

239 blinking, and preparing to begin responding while allowing the EEG recordings to stabilize.

240 Each trial started with a white central fixation cross on top of a gray background that

241 remained in the foreground of the screen throughout the entire trial. Next, an object appeared

242 and remained on the screen for 700 ms (Figure 1). Participants knew to withhold their

243 response at this time. A capital white "T" ("think cue") came on screen for 1700 ms. This

244 timing was based on a similar paradigm (Gruber et al., 2008). Again, no responses were made

245 while the think cue remained on the screen to minimize movement-related artifacts in the

246 EEG data in the time window of interest.

247   Finally, the object reappeared, and the participant was allowed to make a self-paced

248 object recognition judgment (Remember, Feels Familiar, or New; response order

249 counterbalanced). After making their memory judgment, the object remained on the screen

250 but the response scale updated to a confidence judgment (1=highly, 2=moderately,

251 3=somewhat, 4=not at all, Figure 1). This was followed by a four-option forced-choice

252 question about the item's original encoding question (again, the order of the four options was

253 randomized for each subject but remained constant throughout the experiment). Trials were

254 separated by 2 second ITIs with a white fixation cross. For EEG timing precision, the timing

255 of all screens was taken as the ceiling of the expected duration multiplied by the monitor's

256 frame rate.

257

A. encoding
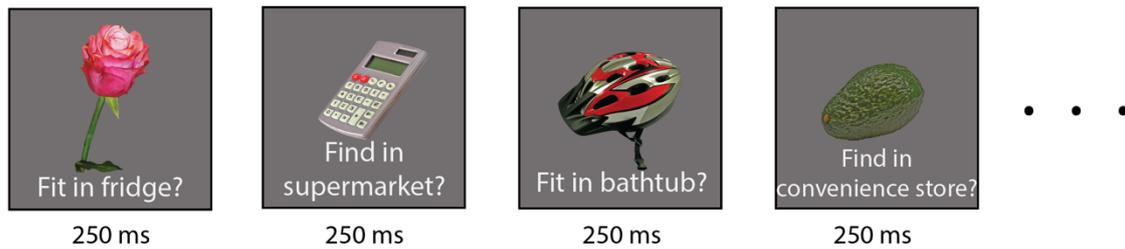
B. item recognition(EEG)
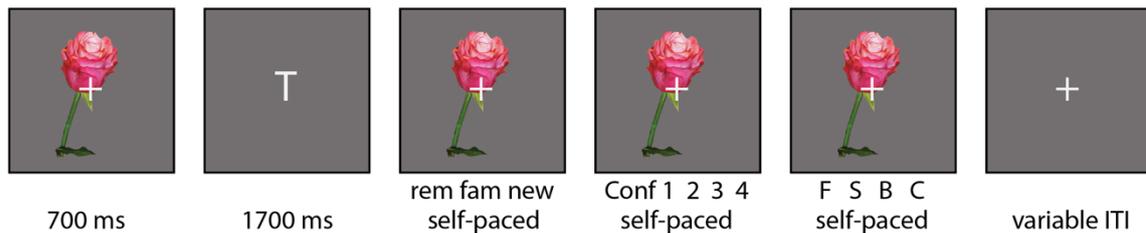
Figure 1. Paradigm design. During the encoding phase (A) participants studied items and answered one of four questions: "Would you find this item in a supermarket/convenience store?", "Would this item fit in a fridge/bathtub?". Items were presented on top of a gray background with questions written in white text. During (B) participants saw old and new items, while undergoing EEG recordings. Items were presented on a gray background with a white fixation cross overlaid. Each item was presented briefly (700 ms). Initial item presentation was followed by a think cue (white letter "T"). Following this, participants made their memory response to the item (rem =Remember, fam =Familiar, new =New item), followed by a memory confidence level judgment and a question source memory judgment ("fridge", "supermarket", "bathtub", "convenience store"; abbreviated above in figure as "F S B C"). ERPs were recorded during the item recognition phase. Black outlines are for figure visualization purposes only and did not appear during the task to participants.

Behavioral measures

Behavioral measures of recollection and familiarity were calculated using dual process estimates, which are intended to give an independent measure of these two processes, while accounting for response bias (Yonelinas, 2002). Recollection was estimated as the difference between the Remember hit rate and the Remember false alarm rate (*[count of all remembered trials / count of all old items] – [count of all remembered false alarms / count of all new items]*) and familiarity was estimated as the difference between the Familiar hit rate corrected by the inverse Remember hit rate and Familiar false alarm rate corrected by the inverse Remember false alarm rate (*[Familiar hit rate / (1 – Remember hit rate)] – [Familiar falsealarm rate / (1 – Remember false alarm rate)],*(Yonelinas, 2002). Source judgments to old items were computed to determine whether participants could retrieve information about

9

284   the question. We expected that accurate retrieval of the orienting task used to encode each

285   item (source memory) should be more likely for items judged as recollected (MacKenzie et

286   al., 2018; Yonelinas, 2002) than for items associated with "familiar" responses.

287

288   ***EEG acquisition and analysis***

289   EEG data were recorded in a sound attenuated chamber at a rate of 512 Hz using a

290   BioSemi (http://www.biosemi.com) ActiveTwo system with 64 active Ag/AgCl scalp

291   electrodes embedded in an elastic cap in an extended version of the international 10/20

292   system. Additional electrodes were placed at the left and right mastoids to be used for offline

293   re-referencing. In addition, the electrooculogram (EOG) was recorded with an additional four

294   electrodes – bipolar vertical channels located approximately 1cm above and below the

295   subject's left eye and horizontal ocular channels located approximately 1 cm lateral to the

296   outer canthus of each eye. The EEG was recorded relative to a common mode sense active

297   electrode near Cz for online referencing. Participants were instructed to blink normally while

298   maintaining focus at the center of the screen and while minimizing muscle tension and any

299   large movements.

300   EEG data preprocessing and analyses were performed using EEGLab (Delorme and

301   Makeig, 2004), ERPLab (Lopez-Calderon and Luck, 2014), and custom code implemented in

302   MATLAB r2014b (www.mathworks.com) for EEG processing, available in a public github

303   repository (https://github.com/hallez/eetemp_eeg_pub/tree/main). Data intended for ERP

304   analyses were downsampled offline to 128 Hz, re-referenced to the average of the mastoid

305   channel signals, and high-pass filtered at 0.1 Hz (IIR Butterworth filter, half-amplitude

306   cutoff=0.2 Hz, slope=12 dB/octave). The data were separately high-pass filtered for ICA

307   (Winkler et al., 2015) at 1Hz (IIR Butterworth filter, half-amplitude cutoff=1.60 Hz, slope=12

308   dB/octave), based on Makoto Miyakoshi's preprocessing pipeline

309   (https://sccn.ucsd.edu/wiki/Makoto's_preprocessing_pipeline). Next, bad channels were

310   detected using the *trimOutlier* function (lower standard deviation threshold=2; upper standard

311   deviation threshold=200) and then epoched (epoch start = -500ms; epoch end = 1000ms).

312   After epoching, outlier epochs were automatically rejected using a thresholded approach

313   implemented with *pop_jointprob* (local channel threshold = 6; global threshold = 2).

314   Independent component analysis (ICA) was performed with the *runica* algorithm (Delorme et

315   al., 2007) holding out mastoid and outlier channels, and the SASICA toolbox (Chaumon et

316   al., 2015)was used to manually review and identify eyeblink-related components for removal

317   from the data. At manual review, any additional epochs or channels that were determined to

318   be outliers were identified for removal or interpolation, respectively. Bad channels were

319   interpolated from the ICA corrected data (mean number of interpolated channels was 1.3±1.9

320   per block). At this point, all six blocks were merged into a single file. Baseline correction was

321   applied to each trial using a pre stimulus period from 200 ms prior to the onset of the first

322   image in a trial. Average number and standard deviation (with the range provided in

323   parentheses) of trials included in the analysis was: 66±12 (34-83), 54±15 (33-94), and 79±24

324   (30-127) for Correct Rejection, Familiar, and Remember trial types, respectively. Raw and

325   preprocessed files can be found at https://osf.io/4e3pq/.

326   Given that ERPs related to long-term memory are known to shift their latency and

327   distribution with different types of stimuli (Addante et al., 2012b; Busch et al., 2004; Taylor,

328   2002; Yonelinas, 2002), we performed non-parametric cluster-based permutation analysis

329   (Maris and Oostenveld, 2007) implemented in the FieldTrip Matlab toolbox (Oostenveld et

330   al., 2011), which corrects for the multiple comparisons problem (MCP) arising from the fact

331   that the effect of interest (i.e. a difference between experimental conditions) is evaluated at

332   large number of data points, here: (channel, time)-pairs. The approach combines neighboring

333   values that are likely to be correlated (e.g., neighboring time points and/or spatial locations) to

334   reduce the problem of multiple comparisons. Therefore, this method allowed us to compare

335   ERPs between trial types (Familiar, Remember, and Correct Rejection) for each (channel,

336   time) data pair and identify statistically meaningful differences. Under the null hypothesis of

337   exchangeability, assuming averages from Familiar, Remember, and Correct Rejection trials

338   are drawn from the same probability distribution, cluster alpha p =0.05 and 0-700 ms time

339   window were used. In order to isolate familiarity and recollection electrophysiological

340   estimates while controlling for other cognitive processes that are not related to memory, ERPs

341   from the following trial types were compared: Familiar as compared to Correct Rejection

342   trials, and Remember as compared to Familiar trials, respectively. Such comparisons are

343   widely used in the studies of old-new effect, including Remember/Know procedures (Duarte

344   et al., 2006, 2004).

345   The comparisons between each pair of trial types were performed via a two-tailed t-

346   test (alpha = 0.05) using *depsamplesT* function, which clustered samples whose t-value was

347   larger than a priori threshold (P=0.05) on the basis of temporal and spatial adjacency. Cluster-

348   level statistics were calculated by taking the sum of the t-values within every cluster and the

349   maximum of the cluster-level statistics was taken. Monte Carlo correction for the MCP with

350   1000 draws from the permutation distribution was used. Channel neighbors for spatial

351   clustering were found based on the template method, using 'Biosemi64_neighb' template.

352   In order to test our critical question of whether ERP signatures associated with

353   recollection and familiarity are associated with dual process estimates, we computed

354   correlations between these measures. This was also performed using a non-parametric cluster-

355   based permutation test. In this case, *Ft_statfun_correlationT* function and Pearson *r*

356   coefficient were used in order to test if there was a relationship between familiarity and

357   recollection dual process estimates per subject (quantitative independent variable) and their

358   (channel, time) EEG data (dependent variable). The correlations of both difference waveforms

359   (Familiar – Correct Rejection, and Remember – Familiar) with behavioral estimates of

360   familiarity and recollection, as generated from dual process estimates, were tested.

361

362   **Results**

363   ***Behavioral results***

364   Participants were highly accurate at discriminating studied from unstudied objects

365   (Table 1). To account for response bias, we also computed dual process estimates of

366   familiarity and recollection (Yonelinas, 2002). Mean familiarity and recollection estimates are

367   presented in Table 1. Each studied item was scored according to the item recognition

368   judgment and accuracy for the question type the item had been paired with (Table 1). The

369   accuracy of source memory was significantly above chance for both familiarity ($t_{37} = 7.0$, *P*<

370   0.001) and recollection ($t_{37} = 10.3$, *P*< 0.001), but participants were significantly more likely

371   to correctly retrieve source information for Remember than Familiar trials ($t_{37}= 6.0$, *P*<

372   0.001). These findings are in agreement with other work showing that accurate source

373   judgments can be made on the basis of both recollection and familiarity (Addante et al.,

374   2012b; Diana et al., 2011, 2008), but that retrieval of contextual details should be more likely

375   when an item is recollected, as compared with familiarity-based recognition (for a

376   comprehensive review, see Yonelinas, 2002).

377

378 **Table 1.** Behavioral results of object recognition and source memory performance. (A)
379 Proportion of "remember" and "familiar" responses to old and new items presented as hit
380 rates, false alarm rates, and source memory rates are presented (with standard deviations)
381 separately for "remember" and "familiar" responses. (B) Mean behavioral estimates of
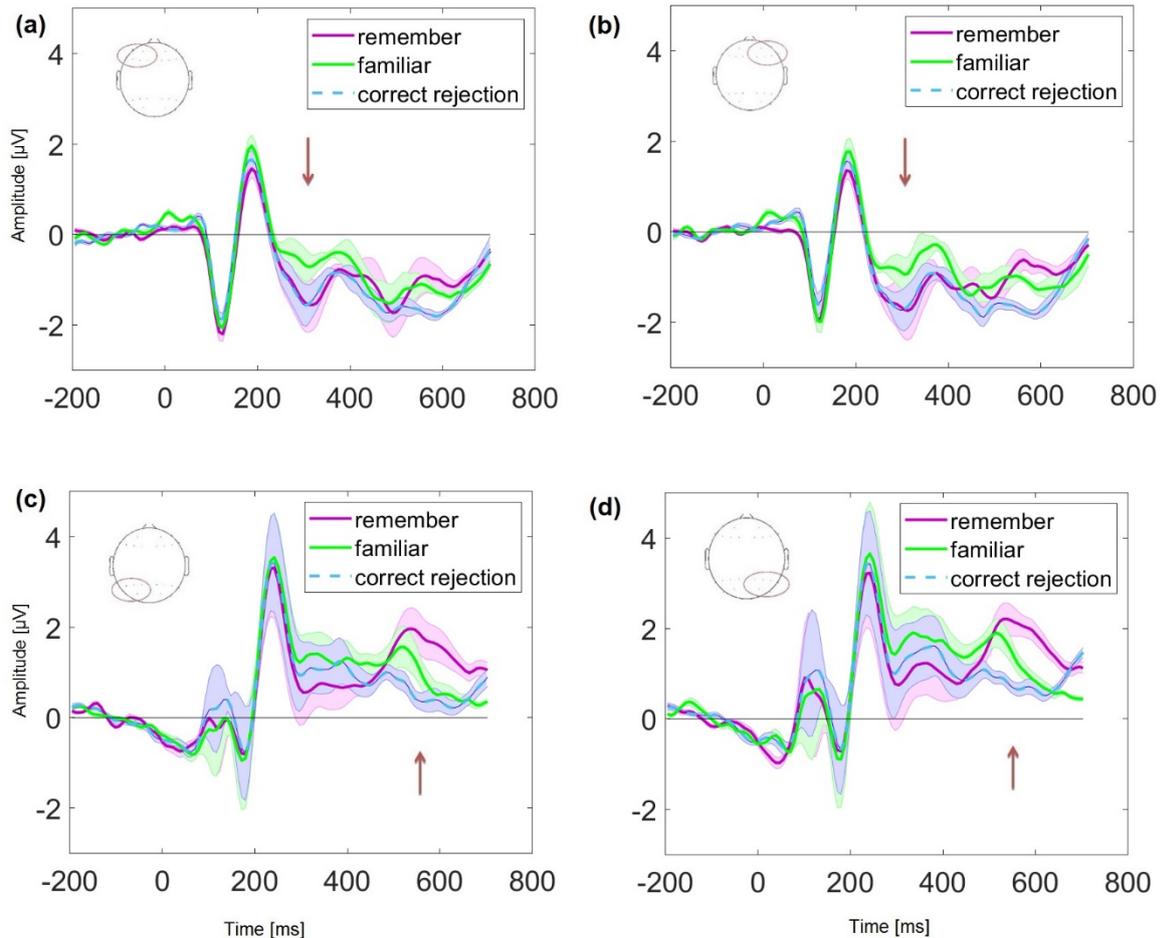382 recollection and familiarity derived from the dual process model are presented (with standard
383 deviations).

(A)		Remember	Familiar
Object recognition performance	Hit rate	0.47±0.14	0.32±0.08
	False alarm rate	0.03±0.05	0.18±0.10
Source memory accuracy		0.47±0.13	0.33±0.07
(B)		Recollection	Familiarity
Dual process estimate		0.44±0.12	0.45±0.15

384

ERP results

386   Before analyzing individual differences in ERP correlates of recognition, we

387 conducted analyses to examine overall ERP old-new effects in order to be able to compare our

388 results to previous reports of ERP differences between recollection and familiarity. We

389 separately averaged ERPs for successfully recognized items associated with Remember

390 responses, for recognized items associated with Familiar responses, and for Correct Rejection

391 responses (Figure 2). These averages were done solely for visualization purposes. We report

392 statistical comparisons between conditions in the following section. Averaged ERPs revealed

393 a sustained negative deflection for all trials types, beginning approximately at 220 and lasting

394 until around 400 ms, (Figure 2a-b) and a positive deflection from approximately 500 to 700ms

395 after stimulus onset (Figure 2c-d).

396

Figure 2. ERP correlates of recollection and familiarity. Grand averaged ERPs on Remember (purple), Familiar (green) and Correct Rejection (dashed blue) trials are separately averaged for four groups of channels split by frontal and parietal for each hemisphere (Woodruff et al., 2006). Arrows are meant to delineate time periods of interest, but do not indicate statistical comparisons: (a) left frontal (F1, F3, F5, F7, AF3, AF7), (b) right frontal (F2, F4, F6, F8, AF4, AF8), (c) left parietal (P1, P3, P5, P7, PO3, PO7), and (d) right parietal (P2, P4, P6, P8, PO4, PO8). Shaded areas represent standard deviation of the mean. Note that these average traces from electrode groups are presented for visualization purposes, but electrodes were analyzed separately in the data-driven statistical analyses.

In addition, to better visualize the familiarity and recollection ERP effects, we also present difference waveforms: Familiar-minus-Correct Rejection and Remember-minus-Familiar (Supplemental figure 3).
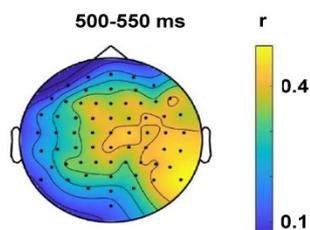
To quantify ERP correlates of familiarity at the group level, we contrasted ERPs associated with familiar responses against ERPs associated with correct rejection responses. As described in the *Methods*, these, and all subsequent ERP analyses, were done using a data-driven non-parametric cluster-based permutation analysis procedure (Maris and Oostenveld, 2007). This method allows us to identify statistically significant differences between

14

416 conditions, though it does not permit specific conclusions about the precise temporal or
417 spatial extent of these differences (Sassenhagen and Draschkow, 2019). We can, however,
418 identify the cluster extent in time and location as descriptive information about the observed
419 data. As such, this analysis identified two spatiotemporal clusters that corresponded to the
420 significant difference (p=0.001 cluster corrected for both clusters) in the observed data: from
421 approximately 250 to 450 ms at frontal and fronto-central scalp sites, and from approximately
422 500 to 600 ms over central, centro-parietal, and right fronto-central sites. Figure 3a shows
423 topographic distributions of the ERP differences between familiar and correct rejection trials
424 corresponding to these time windows.

(A)   Overall familiar-correct rejection ERP
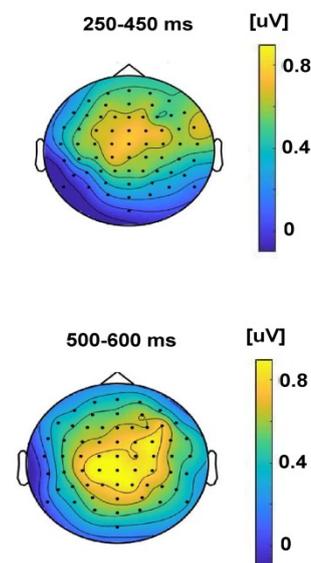
(B)   ERP-behavior correlation

425

426 **Figure 3.** ERP correlates of familiarity. (A) Topographic maps illustrate distributions of mean
427 ERP differences between familiar and correct rejection trials corresponding roughly to the
428 significant clusters identified in the data-driven permutation analysis. (B) A topographic map
429 illustrates a distribution of correlations between familiar - correct rejection ERP differences
430 with dual process estimates of familiarity. Color bars show ERP voltage difference (panel A)
431 or Pearson's r correlation coefficient values (panel B).
432

433   Next, we conducted data-driven analyses to identify ERP correlates of individual

434   differences in familiarity-based recognition. This analysis revealed a significant cluster in the

435   observed data (p=0.001 cluster corrected), extending approximately from 500 to 550 ms

436   (Figure 3b). This correlation was most pronounced over right central and centroparietal areas.

437   For completeness, we also analyzed correlations between familiar – correct rejection ERP

438   differences and behavioral estimates of recollection. These analyses revealed no significant

439   clusters. To summarize, we found that ERPs were sensitive to familiarity-based recognition,

440   both at the overall group level and at the level of individual differences.

441

442   Next, to quantify ERP correlates of recollection, we contrasted ERPs associated with

443   remember hits against ERPs associated with familiar hits. Analyses at the group level

444   revealed significant differences corresponding to two spatiotemporal clusters (p=0.001 cluster

445   corrected for both clusters). The first cluster extended from approximately 250 to 450 ms

446   during which ERPs for remember trials were more negative than ERPs for familiar trials and

447   had widespread scalp topography (Figure 4a upper panel). The second cluster extended from

448   approximately 550 to 700 ms, and manifested as an enhanced positivity for remember trials

449   compared to familiar trials. This latter effect had a centro-parietal scalp topography, largely

450   consistent with prior reports of recollection-related ERP effects (Addante et al., 2012b;

451   Curran, 2000; Duarte et al., 2004; Ranganath and Paller, 2000; Rugg et al., 1998b, 1998a;

452   Rugg and Curran, 2007; Wilding, 2000; Wilding and Ranganath, 2012). Figure 4a shows

453   topographic distributions of the ERP differences between remember and familiar trials during

454   these time windows.

455   Having established significant remember – familiar differences at the group level, we

456   next conducted a data-driven analysis to determine whether ERP differences between these

457   trial types were positively correlated with dual process estimates of recollection. This analysis

458   revealed a significant cluster (p=0.001 cluster corrected) in the observed data extending from

459   600 to 650 ms with a broad scalp distribution, particularly over central and fronto-central

460   scalp sites (Figure 4b), where ERP amplitudes were positively correlated with recollection

461   estimates. For completeness, we also analyzed correlations between remember – familiar ERP

462   differences and behavioral estimates of familiarity. These analyses revealed no significant

463   clusters. To summarize, these analyses revealed significant ERP correlates of recollection at

464   the group level and at the level of individual differences.

465   To exclude a possible explanation of the results hinging on signal-to-noise ratio

466   differences as a function of the number of trials contributing to the ERPs, we reran the

16

467   analysis after equating the number of trials, which resulted in obtaining the same pattern of

468   results. In supplemental figures 4 and 5 we also present topographic maps illustrating

469   correlates of familiarity and recollection for the whole analyzed time window with

470   highlighted electrode clusters on the basis of which the null hypothesis was rejected.
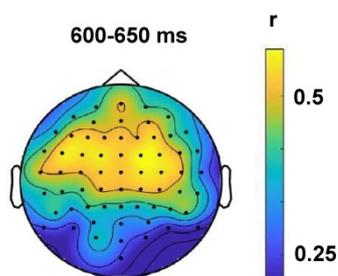
471

472

(A)   Overall remember-familiar ERP
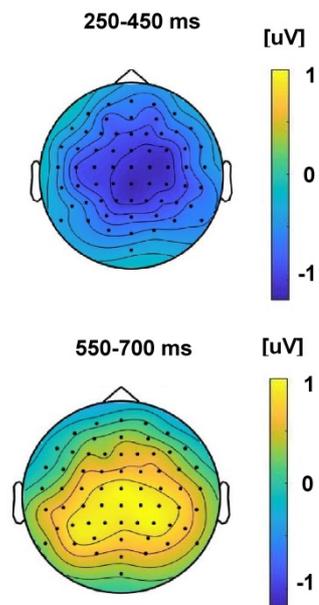
(B)   ERP-behavior correlation

473   **Figure 4.**ERP Correlates of recollection. (A) Topographic maps illustrate distributions of
474   mean ERP differences between remember and familiar trials during time windows that
475   correspond roughly to the significant clusters identified in the data-driven permutation
476   analysis. (B) A topographic map illustrates a distribution of correlations between Remember –
477   Familiar ERP differences with dual process estimates of recollection. Color bars show ERP
478   voltage difference (A) or Pearson's r correlation coefficient values (B).

479

Discussion

481   This study was designed to test the hypothesis that the neural correlates of recollection

482   and familiarity-based recognition are predictive of individual differences in episodic memory

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483   performance. Data-driven analyses of ERPs during memory retrieval revealed overall effects

484   broadly consistent with previous ERP studies of recognition memory, with an early mid-

485   frontal ERP modulation that was enhanced for familiarity-based recognition, and a late

486   posterior ERP modulation that was enhanced for recollection-based recognition. Critically,

487   our data-driven analyses only revealed significant relationships between Familiar– Correct

488   Rejection ERPs and individual familiarity estimates (Figure 3b), whereas we only found

489   significant relationships between Remember – Familiar ERPs and individual recollection

490   estimates (Figure 4b). ERP-behavior correlations were seen at a relatively late latency

491   (>500ms post-stimulus) for both familiarity and recollection. These findings suggest that

492   ERPs can provide useful markers of individual differences in recognition memory processes.

493   Although the central goal of the study was to look at individual differences in behavior

494   and electrophysiology, we first wanted to determine the extent to which our results concurred

495   with results from previous ERP paradigms. Consistent with a large body of evidence from

496   ERP studies of recognition memory, we observed an early ERP old-new effect related to

497   familiarity-based recognition and a late old-new effect related to recollection-based

498   recognition. It is notable, however, that many other recognition memory correlates have been

499   reported with time courses and scalp distributions that vary across paradigms (c.f., Wilding

500   and Ranganath, 2012). This variance makes sense, because processes that support recognition

501   memory can occur within 200 ms of the onset of a word or picture, and there is likely be

502   extensive parallel, feedforward, and feedback processing throughout different brain networks

503   (Clarke et al., 2011; Clarke and Tyler, 2014; Halgren et al., 2006; Marinkovic et al., 2003),

504   resulting in field potentials that overlap in space and time at the scalp. Thus, the use of

505   different types of stimuli (e.g., words, pictures, etc.) or different kinds of memory decision

506   procedures across studies could likely engage different subprocesses that could impact the

507   timing or topography of ERP correlates of memory (Bader et al., 2020; Busch et al., 2004;

508   Taylor, 2002; Yonelinas, 2002).

509   In order to address this concern in an unbiased manner, we adopted a statistical

510   technique, non-parametric cluster-based permutation testing (Maris and Oostenveld, 2007),

511   that relies on the data to determine both significant time windows and electrode clusters. This

512   was also adapted when identifying spatiotemporal clusters that correlate with behavioral

513   memory measures. Our analyses revealed a rich picture, such that two different

514   spatiotemporal clusters were associated with familiarity, and two different clusters were

515   associated with recollection. Although our analysis methods do not permit precise inferences

516   about the timing of these effects, it is notable that recollection and familiarity were each

517   associated with clusters in relatively early and late time windows. This analysis enabled us to

518   identify reliable effects without relying on assumptions from previous work, and, in turn, may

519   have enabled us to uncover the relationships between electrophysiology and memory

520   measures that have been previously mixed in other reports in the literature (Curran et al.,

521   2006; Friedman and Johnson, 2000; Mecklinger, 2006, 2000; Olichney et al., 2000; Paller and

522   Kutas, 1992; Rhodes and Donaldson, 2007; Rugg et al., 1998a; Smith, 1993; Tsivilis et al.,

523   2001; Wilding and Ranganath, 2012). For instance, we identified different neural correlates of

524   familiarity and recollection, but these results did not conform to the expectation (Curran et al.,

525   2006) that familiarity-related neural processes should always precede those related to

526   recollection.

527   A second key finding from this study is that ERPs also tracked individual differences

528   in familiarity- and recollection-based recognition. Again, the use of data-driven approaches

529   revealed results that might not have been obtained by assuming that individual differences in

530   behavior should correlate with the magnitude of well-known ERP old-new effects. As shown

531   in Figure 3, ERP correlations with familiarity estimates were seen over right posterior sites

532   approximately 500-550 ms post-stimulus, a window which overlapped with the time window

533   during which a significant group-level ERP familiarity effect was observed over central sites.

534   Likewise, as shown in Figure 4, ERP correlations with recollection estimates were seen

535   approximately 600-650 ms at frontal scalp sites, a time window that overlapped with a

536   significant group-level ERP recollection effect with a centro-parietal topography.

537   One way to think about these results is that those who had higher behavioral estimates

538   of recollection or familiarity showed ERP effects that were larger in magnitude than those

539   who had lower recollection or familiarity estimates. To explore this possibility, we calculated

540   grand averaged ERPs on remember, familiar and correct rejection trials for low and high

541   (median split) familiarity estimate performers (Supplemental Figure 1) and low and high

542   (median split) recollection estimate performers (Supplemental Figure 2). Both the familiarity

543   (familiar – correct rejection difference within 500-600 ms time window) and recollection

544   effects (remember – familiar difference within approximately 600-700 ms time window) were

545   more pronounced in high than in low performers. Alternatively, it is possible that group-level

546   ERP recollection and familiarity effects overlapped in time from separate ERP components

547   that differentiated between those with high versus low performers. Although the latter

548   possibility is less parsimonious, we cannot conclusively differentiate between topographic

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549   changes driven by increases in the strength of activity in the same configuration of neural

550   sources vs. topographic changes driven by the involvement of different neural sources

551   (Urbach and Kutas, 2002).

552   Our analyses were guided by models which propose that recollection and familiarity

553   independently contribute to successful recognition memory. These models align with a vast

554   body of evidence from lesion, intracranial EEG, and functional neuroimaging evidence

555   demonstrating that familiarity disproportionately depends on representations of item-related

556   information by the perirhinal cortex, whereas recollection disproportionately depends on

557   binding of item and context information by the hippocampus (Davachi, 2006; Eichenbaum et

558   al., 2007; Ranganath, 2010b; Ranganath and Ritchey, 2012). Other researchers, however,

559   have been more agnostic about memory *content*, instead focusing on the idea that all retrieved

560   information is summed together to provide an overall sense of the *strength* of a memory

561   (Kelley and Wixted, 2001; Wixted, 2007). According to this view, "remember" and "familiar"

562   responses reflect different points along a single one-dimensional continuum of memory

563   strength (Kelley and Wixted, 2001). It is important to note that such single-process models do

564   not attempt to characterize memory per se, but rather to account for the way decisions are

565   made on a memory task—for instance, it is possible that there are qualitatively different

566   neural signals for different kinds of memory content, and that the information is integrated

567   into a single strength of evidence signal when making a behavioral response (Gold and

568   Shadlen, 2007, 2001).

569   Our study was not designed to conclusively adjudicate between single- and dual-

570   process models, but it is not clear that a single memory strength process would be sufficient to

571   fully account for our results. If one were to assume that remember and familiar responses vary

572   along a single memory strength continuum, and if ERPs reflect an aggregated measure of

573   memory strength, then we would expect any ERP old-new effect to be larger for remember

574   responses than for familiar responses. However, as we can see from the raw traces in Figure 2,

575   prior to approximately 500 ms, there is an enhanced positivity for familiar trials that is

576   virtually absent for remember trials. This might seem counterintuitive, but it aligns with the

577   dual process model. According to models that assume independent contributions of

578   recollection and familiarity to recognition (Aggleton and Brown, 1999; Atkinson and Juola,

579   1973, 1974; Atkinson et al., 1974; Eichenbaum et al., 1994; Jacoby, 1984, 1991, 1983; Jacoby

580   et al., 1992; Jacoby and Dallas, 1981; Mandler, 1980; Norman and O'Reilly, 2003; Yonelinas,

581   2002, 2001a, 2001b, 1999, 1997, 1994), a familiar response is made only when familiarity is

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582   very high and recollection has failed. A remember response, in turn, happens when

583   recollection is successful, even if the item's familiarity is relatively low. Thus, the model

584   would predict that an ERP correlate of familiarity can be very large on familiar trials and

585   attenuated, or even absent, on remember trials (see also Diana et al., 2011). Moreover, if we

586   solely consider behavioral performance, we can look at the associated, or source, information

587   that can be retrieved when an item is successfully remembered. Although there is evidence

588   that both familiarity and recollection can support accurate source memory (Addante et al.,

589   2012b; Diana et al., 2011, 2008; Yonelinas, 2001a), recollection-based responses are more

590   closely associated with retrieval of contextual details (Diana et al., 2012; Dimsdale-Zucker et

591   al., 2018; Ranganath, 2010b, 2010a; Ranganath and Rainer, 2003). We observed significantly

592   above chance source memory performance for items correctly given both familiar and

593   remember responses. However, source memory performance on familiar trials was

594   significantly lower than for remember trials. This fits with the dual-process account of

595   recognition memory phenomenology (Park and Donaldson, 2019; Yonelinas, 2002, 1994;

596   Yonelinas et al., 2010). Another key point is that recollection dual process estimates only

597   correlated with remember – familiar ERPs and familiarity estimates only with familiar –

598   correct rejection ERPs. Moreover, neither correlation effects overlapped in time and

599   topography. The findings are compatible with a dual-process account. However, we

600   acknowledge that the present non-parametric cluster-based permutation test methods do not

601   allow us to make strong conclusions about the topography and timing of the familiarity and

602   recollection ERP effects.

603   Another controversy in prior ERP studies of recognition memory has focused on the

604   functional significance of the mid-frontal ERP old-new effects (Bridger et al., 2012; Paller et

605   al., 2012, 2007; Voss et al., 2012; Voss and Federmeier, 2011; Voss and Paller, 2006; Yovel

606   and Paller, 2004). Results from many studies have supported the idea that this old-new effect

607   is enhanced during familiarity-based recognition, and that it is relatively insensitive to factors

608   that influence recollection (Addante et al., 2012b; Bridger et al., 2012; Curran, 2004, 2000;

609   Friedman and Johnson, 2000; Park and Donaldson, 2019; Rugg et al., 1998a; Rugg and

610   Curran, 2007; Wilding and Herron, 2006; Wilding and Ranganath, 2012). However, a number

611   of findings also support the idea that the mid-frontal old-new effect could instead reflect

612   conceptual priming, which refers to more fluent processing of conceptual information that has

613   been recently encountered (Guillem et al., 2001; Jelicic, 1995; Levy et al., 2004; Mitchell and

614   Bruss, 2003; Nessler et al., 2005; Olichney et al., 2000; Paller et al., 2012, 2007; Ullsperger et

21

615   al., 2000; Voss and Paller, 2007, 2006). For instance, thinking about the meaning of the word

616   "banana" might make it more likely to come into mind when asked to generate the names of

617   fruit words. Yovel and Paller (2004) used photographs of faces never seen before the

618   experiment as stimuli, to isolate a pure familiarity effect. The authors found no association

619   between familiarity and N400s and suggested that familiarity with faces may arise by a subset

620   of the neural processing responsible for recollection, while the N400 reductions observed in

621   the literature may reflect verbally mediated conceptual priming effects instead of familiarity.

622   Another study (MacKenzie and Donaldson, 2007) obtained similar posterior old/new effect

623   indexing familiarity for faces. However, in contrast to Yovel and Paller, the old/new effects

624   associated with familiarity and recollection were topographically dissociable, consistent with

625   a dual process view of recognition memory.

626   MacLeod and Donaldson (2017) also investigated the functional utility of the left

627   parietal old/new effect using verbal stimuli. Their results revealed that ERP measures (defined

628   as the mean ERP old/new difference within 500-800 ms post-stimulus averaged across left

629   parietal electrodes: P1, P3, and P5) of retrieval were not related to behavioral performance.

630   The authors concluded that the relationship between the left parietal effect and recollection is

631   more complex than previously thought in the sense that the variation in the magnitude of the

632   left parietal old/new ERP effect does not always reliably predict variation in episodic

633   recollection between participants. However, the paper does not fully address the relation

634   between ERPs and behavioral estimates of familiarity and recollection for several reasons: (1)

635   the ERP effect was restricted only to the late left parietal effect, (2) the behavioral measures

636   of recollection used in this study does not dissociate recollection from familiarity, and (3)

637   only 20 participants were included in the correlation of R/K effect magnitude with behavioral

638   data.

639   More recently, Wang et al. (2020) employed conceptually impoverished items

640   (kaleidoscope images) as stimuli in a recognition memory test with a modified

641   Remember/Know paradigm and they also observed that ERPs for Know hits were more

642   positive than those for Correct Rejection items within 500-800 ms. Putting all these results

643   together, there is considerable evidence suggests that the N400-like ERP effects are

644   modulated by conceptual priming and familiarity (Bader and Mecklinger, 2017; Nessler et al.,

645   2005; Wolk et al., 2004).

646   The controversy over ERP correlates of familiarity and conceptual priming relates to

647   the broader question regarding the relationship between fluent processing and familiarity-

648   based recognition memory. Substantial evidence exists to suggest that neural processes

649   associated fluent processing of conceptual information are also related to familiarity—for

650   instance, N400-like potentials occur in the perirhinal cortex during both conceptual priming

651   and recognition memory (Nobre and McCarthy, 1995, 1994; Staresina et al., 2012).

652   Moreover, damage to the left perirhinal cortex impairs both conceptual priming and

653   familiarity-based recognition memory (Bowles et al., 2007; Wang and Yonelinas, 2012a,

654   2012b; Wang et al., 2010). Finally, fMRI studies have shown that activity in the left perirhinal

655   cortex during encoding predicts both conceptual priming and familiarity-based recognition,

656   and perirhinal activity has been correlated with behavioral performance on both conceptual

657   priming and familiarity-based recognition measures (Dew and Cabeza, 2013; Diana et al.,

658   2010; Haskins et al., 2008; Heusser et al., 2013; Ranganath et al., 2004; Voss et al., 2009;

659   Wang et al., 2015, 2014). Although these findings do not rule out the possibility that

660   conceptual priming and familiarity can be dissociated (Paller et al., 2012), they are consistent

661   with the broader idea that fluent processing of an item's conceptual features can contribute to

662   one's subjective sense that the item is familiar (Mecklinger and Bader, 2020; Taylor and

663   Henson, 2012; Wang and Yonelinas, 2012b).

664   In summary, the current study presents evidence to suggest that ERPs can be used to

665   identify neural correlates of recollection and familiarity, both at the group level, and at the

666   level of individual differences. The present findings provide support for the idea that ERPs

667   can be used as biomarkers of underlying memory processes in healthy individuals, patient

668   populations, or specific populations, like older adults or children (MacLeod and Donaldson,

669   2017). The combined use of behavioral and ERP measures, as in the present study, might be

670   especially useful in the identification of those who are at risk for disorders such as

671   Alzheimer's disease (Xia et al., 2020). Additionally, the present results also highlight the

672   potential value of data-driven analysis methods as a means to identify neural correlates of

673   cognitive processes, complementing approaches that focus on specific, well-characterized
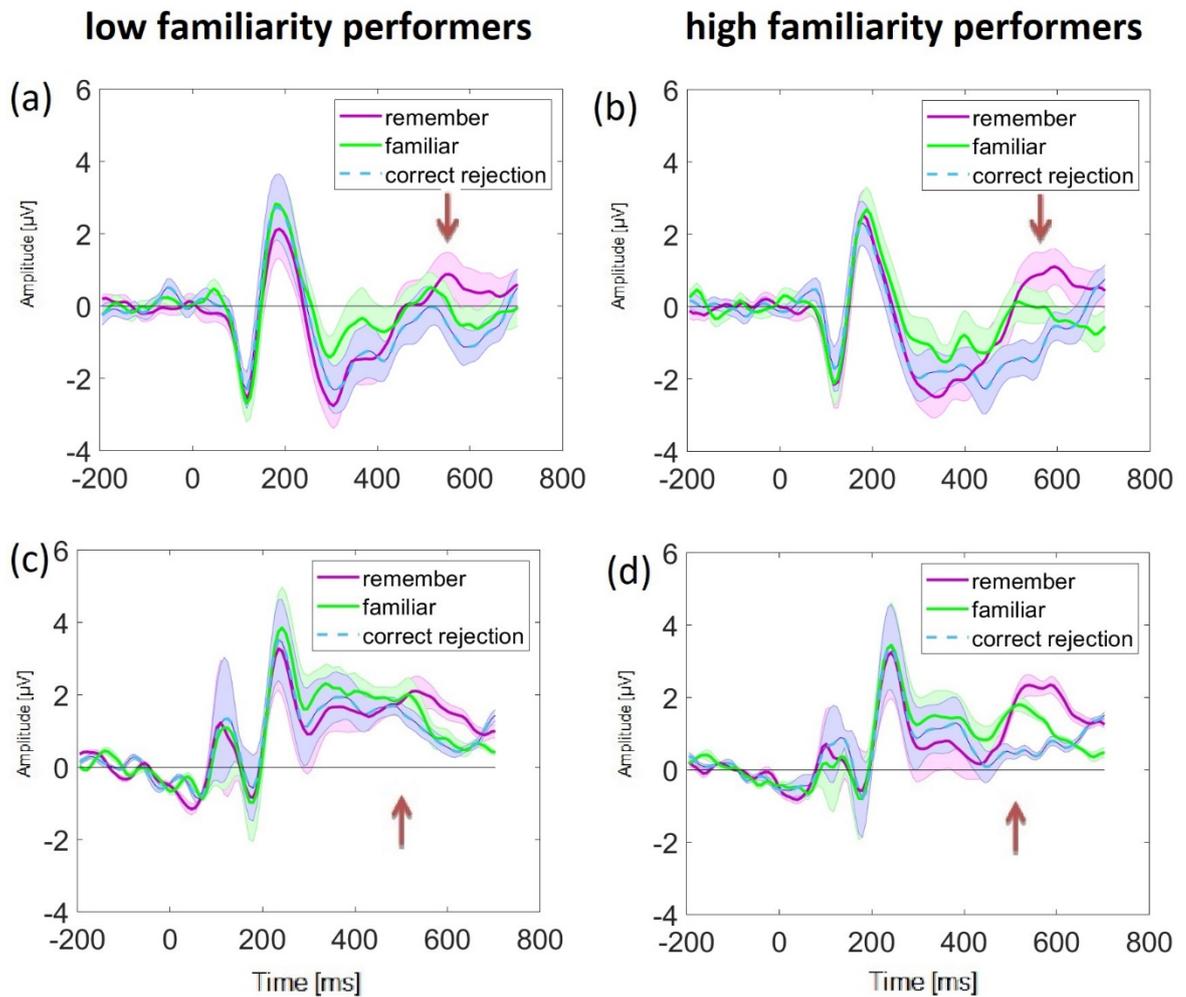
674   components.

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688   Supplementary materials

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Supplemental Figure 1. ERP correlates of familiarity. Grand averaged ERPs on Remember
(purple), Familiar (green) and Correct Rejection (dashed blue) trials for low and high
performers based on median split. Shaded areas represent standard deviation of the mean.
Arrows are meant to delineate time periods of interest, but do not indicate statistical
comparisons: (a) low familiarity estimate performers at Cz, (b) high familiarity estimate
performers at Cz, (c) low familiarity estimate performers at right parietal (P2, P4, P6, P8,
PO4, PO8), and (d) high familiarity estimate performers at right parietal (P2, P4, P6, P8, PO4,
PO8). Note that the average traces from electrode groups are presented for visualization
purposes, but electrodes were analyzed separately in the data-driven statistical analyses.

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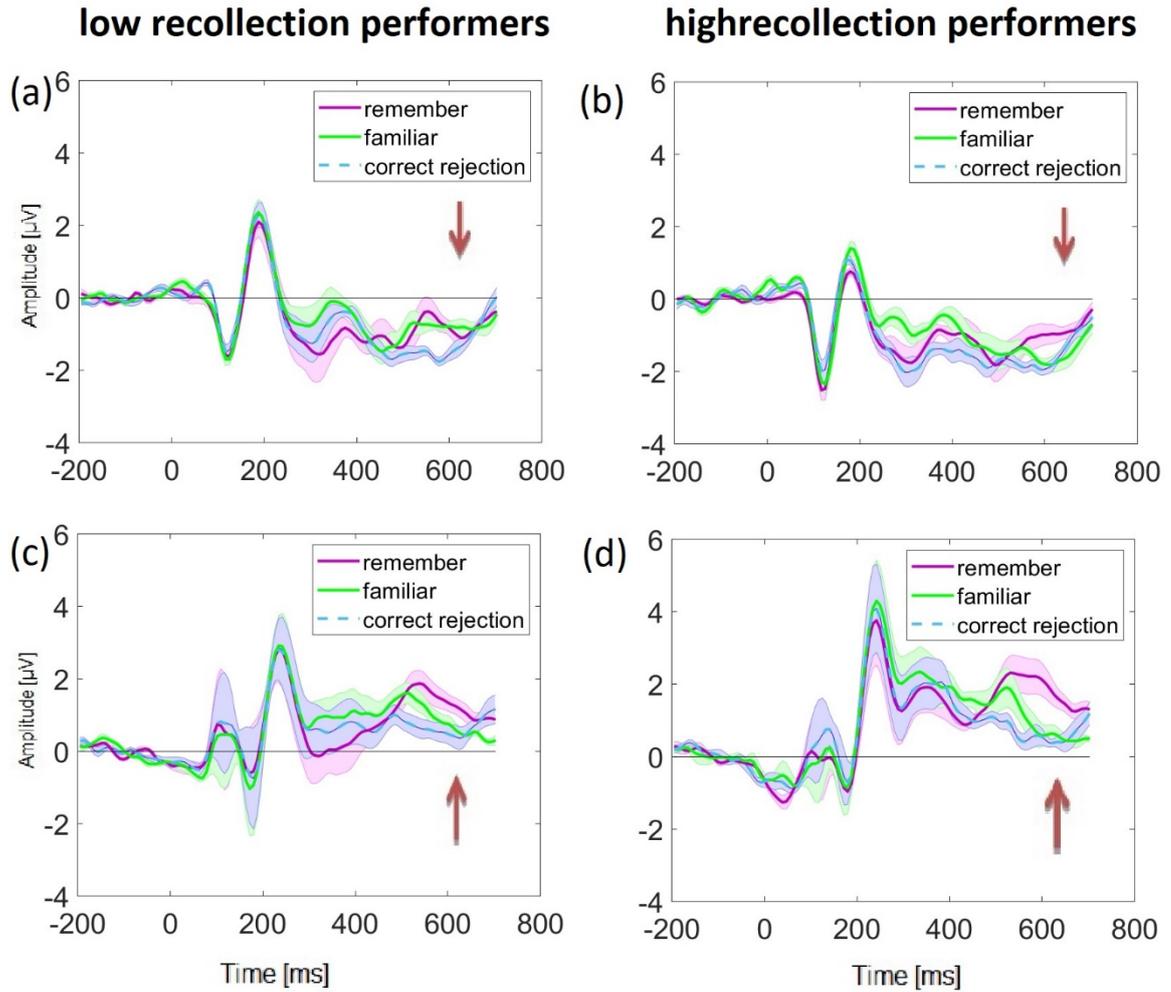
Supplemental Figure 2. ERP correlates of recollection. Grand averaged ERPs on Remember (purple), Familiar (green) and Correct Rejection (dashed blue) trials for low and high performers based on median split. Shaded areas represent standard deviation of the mean. Arrows are meant to delineate time periods of interest, but do not indicate statistical comparisons: (a) low recollection estimate performers at frontal (F1, F3, F5, F7, AF3, AF7, F2, F4, F6, F8, AF4, AF8), (b) high recollection estimate performers at frontal (F1, F3, F5, F7, AF3, AF7, F2, F4, F6, F8, AF4, AF8), (c) low recollection estimate performers at parietal (P1, P3, P5, P7, PO3, PO7, P2, P4, P6, P8, PO4, PO8), and (d) high recollection estimate performers at parietal (P1, P3, P5, P7, PO3, PO7, P2, P4, P6, P8, PO4, PO8). Note that the average traces from electrode groups are presented for visualization purposes, but electrodes were analyzed separately in the data-driven statistical analyses.

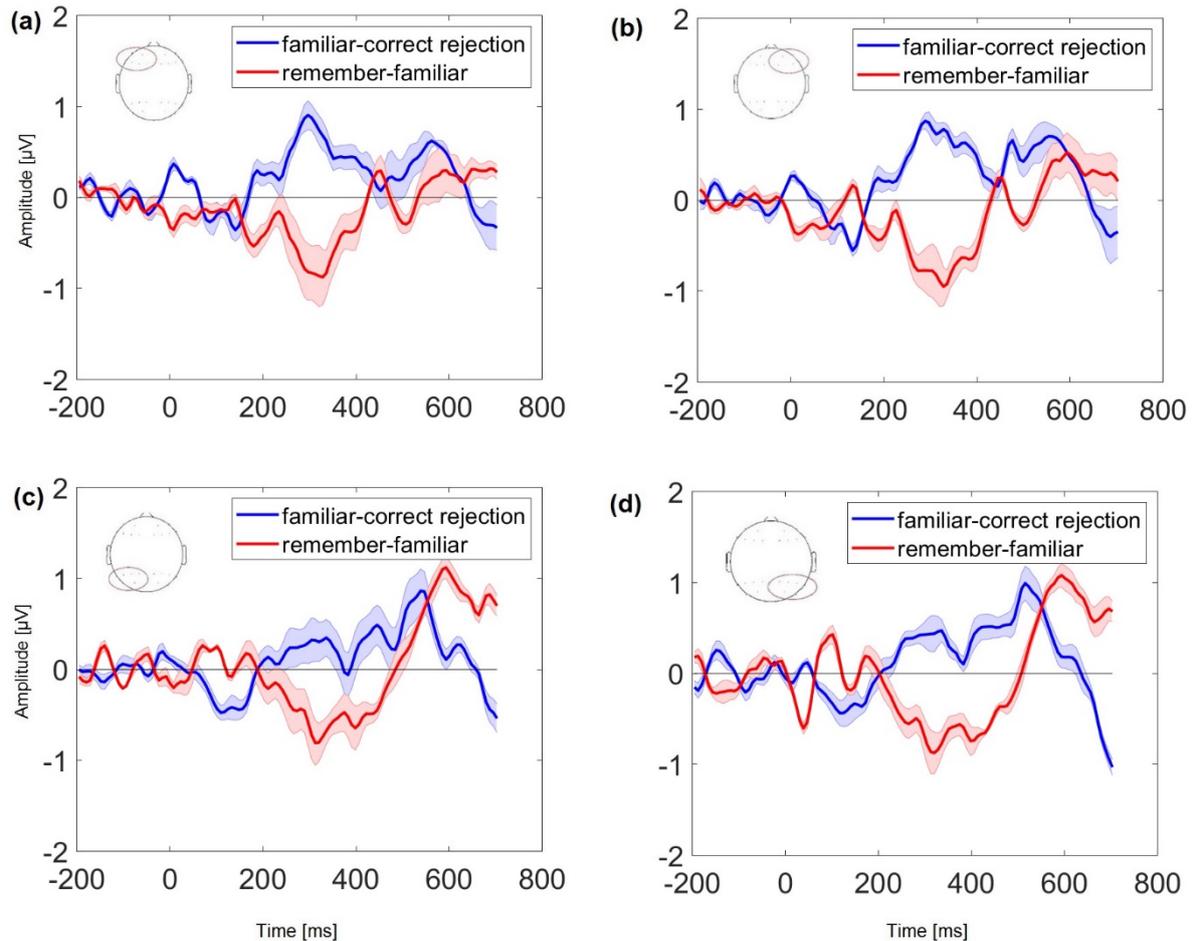**Supplemental figure 3.** ERP correlates of recollection and familiarity. Grand averaged ERP difference waveforms: Familiar-minus-Correct Rejection (red) and Remember-minus-Familiar (blue), separately averaged for four groups of channels split by frontal and parietal for each hemisphere (Woodruff et al., 2006): (a) left frontal (F1, F3, F5, F7, AF3, AF7), (b) right frontal (F2, F4, F6, F8, AF4, AF8), (c) left parietal (P1, P3, P5, P7, PO3, PO7), and (d) right parietal (P2, P4, P6, P8,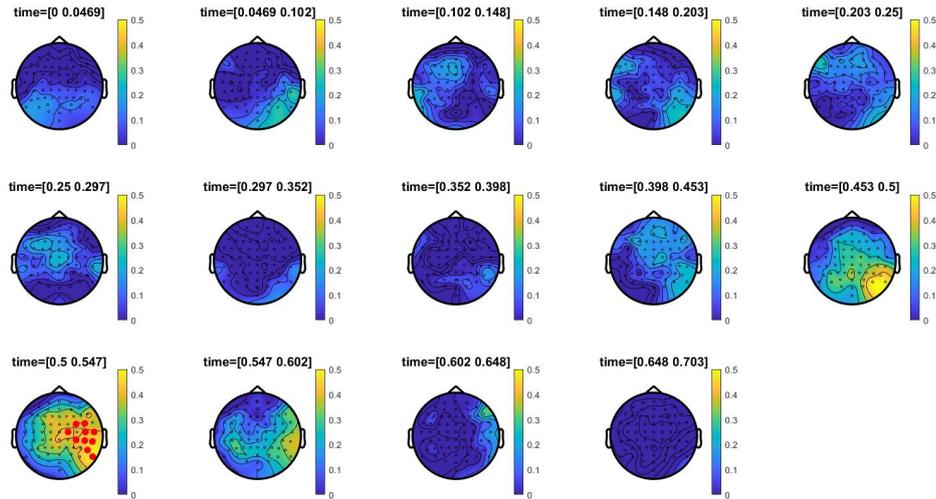 PO4, PO8). Shaded areas represent standard deviation of the mean. Note that these average traces from electrode groups are presented for visualization purposes, but electrodes were analyzed separately in the data-driven statistical analyses.
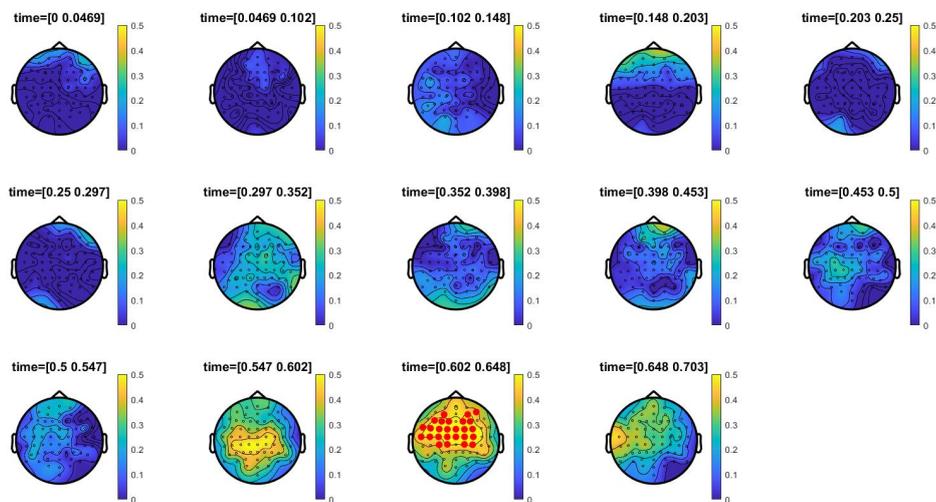
Supplemental figure 4. ERP correlates of familiarity. Topographic maps illustrate a distribution of correlations between Familiar - Correct Rejection ERP differences with dual process estimates of familiarity for 50 ms time bins. Electrode clusters on the basis of which the null hypothesis was rejected are highlighted with red asterisks. All timepoints and all 64 electrodes were included in the permutation test within specified 0-700 ms time window, at $P < 0.05$, cluster corrected. Color bars show Pearson's r correlation coefficient values.

Supplemental figure 5. ERP Correlates of recollection. Topographic maps illustrate a distribution of correlations between Remember – Familiar ERP differences with dual process estimates of recollection for 50 ms time bins. Electrode clusters on the basis of which the null hypothesis was rejected are highlighted with red asterisks. All timepoints and all 64 electrodes were included in the permutation test within specified 0-700 ms time window, at $P < 0.05$, cluster corrected. Color bars show Pearson's r correlation coefficient values (B).

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Item response (scored)	Highly confident	Moderately confident	Somewhat confident	Not at all confident
Recollect	66.36 (27.18)	20.91 (14.21)	4.19 (3.25)	1.33 (0.58)
Familiar	19.06 (14.06)	18.42 (6.33)	16.97 (8.84)	3.76 (3.07)
Miss	9.93 (9.18)	12.53 (8.25)	9.97 (5.88)	2.89 (2.35)
Correct rejection	28.91 (19.59)	24.39 (12.25)	13.33 (7.88)	4.11 (2.83)

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746 **Supplemental Table 1.** Mean and standard deviation counts of confidence level by scored
747 item response.

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