1 **Alpha Phase Dynamics Predict Age-Related Visual Working Memory Decline**

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Abstract

Alpha oscillations are modulated in response to visual temporal and spatial cues, However, the neural response to alerting cues is less explored, as is how this response is affected by healthy aging. Using scalp EEG, we examined how visual cortical alpha activity relates to working memory performance. Younger (20-30 years) and older (60-70 years) participants were presented with a visual alerting cue uninformative of the position or size of a lateralized working memory array. Older adults showed longer response times overall, and reduced accuracy when memory load was high. Older adults had less consistent cue-evoked phase resetting than younger adults, which predicted worse performance. Alpha phase prior to memory array presentation predicted response time, but the relationship between phase and response time was weaker in older adults. These results suggest that changes in alpha phase dynamics, especially prior to presentation of task-relevant stimuli, potentially contribute to age-related cognitive decline.

In order to achieve high behavioral performance, limited attentional resources must be efficiently directed towards task-relevant information. Such information could include the timing or spatial position of upcoming visual stimuli. Knowledge of when[1] or where[2] a target will appear enhances detection and shortens response times. Likewise, presentation of neutral warning cues improves response times by heightening alertness or preparedness for upcoming stimuli. The effects of informative temporal and spatial cues are strongly related to the dynamics of 7-14-Hz alpha oscillations, as observed in anticipatory changes in alpha amplitude[3-6] and phase[7]. How alpha dynamics are modulated in response to noninformative alerting cues is less understood.

Neurologically healthy aging is associated with declines in attention and working memory. Behaviorally, the benefits of spatial cuing are relatively resistant to healthy aging[8,9], but older adults derive less benefit from the presence of temporal[5] and alerting cues[10,11]. Physiologically, older adults show reduced alpha modulation in response to temporal[5] and spatial cues[12], though a recent study found no age-related differences in neural response to alerting cues[13]. However, because alpha activity was not examined in that study, it is unclear whether older adults' reduced use of alerting cues can be predicted by concomitant changes in alpha oscillatory dynamics.

To investigate alpha response to alerting cues, and how this response is affected by healthy aging, we recorded EEG from younger and older adults performing a unilateral visual working memory task. Each trial of the task included an alerting cue signaling the upcoming presentation of a lateralized memory array. This cue allowed us to probe participants' preparedness for upcoming stimuli independent of motor preparation. We hypothesized that age-related changes in neural activity would manifest themselves in the alpha amplitude and phase response to presentations of the alerting cue. We also hypothesized that the extent to which neural response to the alerting cue was altered would also predict declines in working memory performance.

Results
Behavior

89   **Response Time.** We compared younger and older adults' response times (RTs) on a
90   lateralized visual working memory task (Fig. 1a, see Methods). RTs showed main
91   effects of age (Fig. 1b, $F_{1,29}$ = 13.32, p = 0.0010, generalized η^2 = 0.31) and memory
92   load ($F_{2,58}$ = 67.20, Greenhouse-Geisser (GG) ε = 0.88, $p_{GG} < 10^{-13}$, η^2 = 0.089) and an
93   interaction between age and memory load ($F_{2,58}$ = 3.75, ε = 0.88, p_{GG} = 0.029, η^2 =
94   0.0054). Between groups, younger adults had faster RTs than older adults in each load
95   condition. This included load-one (541 ms vs. 643 ms, mean difference 95% confidence
96   interval [-166 ms, -39 ms], $t_{28.91}$ = -3.29, p = 0.0027, Cohen's d = -1.17), load-two (565
97   ms vs. 670 ms, [-166 ms, -44 ms], t_{29} = -3.51, p = 0.0015, Cohen's d = -1.24), and load-
98   three conditions (591 ms vs. 721 ms, [-195 ms, -65 ms], t_{29} = -4.09, $p < 10^{-3}$, Cohen's d
99   = -1.45).

101   **Accuracy.** As assessed using the sensitivity measure d', accuracy showed an effect of
102   memory load (Fig. 1c, $F_{2,58}$ = 51.04, ε = 0.92, $p_{GG} < 10^{-11}$, η^2 = 0.16) and an interaction
103   between age and memory load ($F_{2,58}$ = 5.78, ε = 0.83, p_{GG} = 0.0065, η^2 = 0.021).
104   Accuracy was comparable between younger and older adults in load-one (p =
105   0.73, Cohen's d = 0.13) and load-two conditions (p = 0.22, Cohen's d = 0.45). However,
106   younger adults outperformed older adults in load-three conditions (3.32 vs. 2.58, [0.042,
107   1.45], $t_{29.00}$ = 2.17, p = 0.039, Cohen's d = 0.77). In summary, older adults showed
108   slower RTs overall and reduced working memory accuracy specifically during high-load
109   trials.

111   **EEG**
112   **Alerting Cue Activity.** To investigate neurophysiological measures potentially
113   underlying decreased behavioral performance in older adults, we first examined
114   younger and older adults' neural response to presentations of the alerting cue. During
115   task performance, younger and older adults exhibited 7-14 Hz oscillatory alpha activity
116   in visual parietal-occipital regions (Fig. 2a). Based on participants' peak alpha
117   frequency, previously shown to be lower in older adults[14], we determined individualized
118   alpha bands and compared participants' normalized alpha analytic amplitude and
119   instantaneous phase activity during the task. To examine the consistency in alpha
120   phase activity across trials, we also computed alpha intertrial coherence (ITC) per
121   participant.
122   Parietal-occipital visual regions showed alpha amplitude and ITC response to
123   presentations of the alerting cue (Fig. 2b, 2c). Alpha amplitude modulation in response
124   to the alerting cue (-350 to 0 ms) showed no effects of age ($F_{1,29}$ = 2.82, p = 0.10, η^2 =
125   0.074), hemisphere ($F_{1,29} < 1.0$), or memory load ($F_{2,58} < 1.0$). This lack of hemisphere
126   and memory load effect is consistent with the alerting cue being uninformative of the
127   lateral position and number of upcoming stimuli.
128   Compared to baseline (-500 to -350 ms), alpha ITC increased in response to the
129   alerting cue in both younger and older adults. Using a resampling procedure to compare
130   cue-evoked to baseline ITC on a per-subject basis, we determined that all 17 younger
131   adults, as well as 11 out of 14 older adults, showed cue-evoked increases in ITC ($p <$
132   10^{-4} for all). These increases in ITC suggest the presence of stimulus-evoked alpha

133   phase resets in both younger and older adults. As with alpha amplitude, cue-evoked ITC
134   did not show an effect of hemisphere ($F_{1,29} < 1.0$) or memory load ($F_{2,58} < 1.0$), again
135   consistent with the noninformative nature of the alerting cue. However, younger adults
136   had higher cue-evoked ITC than did older adults (Fig. 3a, 3b, 0.63 vs. 0.23, [0.24, 0.56],
137     $F_{1,29} = 23.64$, $p < 10^{-4}$, $\eta^2 = 0.32$).
138
139   **Memory Array Activity.** Younger adults also showed alpha response to presentation of
140   the memory array. After memory array onset, alpha amplitude diverged between
141   hemispheres in younger and older adults (Fig. 2b). Mean alpha amplitude (0 to 400 ms)
142   showed main effects of memory load (Fig. 4a, 4b, $F_{2,58} = 4.29$, $\varepsilon = 0.87$, $p_{GG} = 0.024$, η^2
143     $= 0.011$) and hemisphere ($F_{1,29} = 18.15$, $p < 10^{-3}$, $\eta^2 = 0.034$) and an interaction
144   between age and hemisphere ($F_{1,29} = 9.10$, $p = 0.0053$, $\eta^2 = 0.017$). Post hoc analysis
145   revealed that alpha amplitude decreased from load-one to load-two ([0.0053, 0.056], t_{30}
146     $= 2.47$, $p = 0.019$, Cohen's $d = 0.44$), but not from load-two to load-three conditions ($p =$
147   0.37, Cohen's $d = 0.17$). In addition, alpha lateralization, or the difference in alpha
148   amplitude between hemispheres, was greater in younger than older adults (0.11 vs.
149   0.019, [0.034, 0.15], $t_{23.21} = 3.22$, $p = 0.0038$, Cohen's $d = 1.09$).
150   As with alerting cue presentation, memory array presentation also caused alpha
151   phase resets (Fig. 2c). Overall, 15 of 17 younger adults as well as 12 of 14 older adults
152   showed array-evoked ITC ($p < 10^{-4}$ for all). Unlike with cue-evoked ITC, array-evoked
153   ITC showed no effects of memory load ($F_{2,58} < 1.0$), age ($F_{1,29} = 1.60$, $p = 0.22$, $\eta^2 =$
154   0.028), or hemisphere ($F_{1,29} < 1.0$).
155
156   **Contralateral Delay Activity.** We also investigated participants' contralateral delay
157   activity (CDA), an event-related potential measure indicative of working memory
158   capacity[15,16] and top-down attentional processes[17-20]. We observed sustained delay-
159   period (300 to 900 ms) negativity in the hemisphere contralateral to the memory array
160   (Fig. 5a). This negativity or CDA showed a main effect of memory load (Fig. 5b, $F_{2,58} =$
161   14.88, $\varepsilon = 0.96$, $p_{GG} < 10^{-5}$, $\eta^2 = 0.080$), wherein CDA increased in magnitude from load-
162   one to load-two conditions ([0.34 μV, 0.86 μV], $t_{30} = 4.66$, $p < 10^{-4}$, Cohen's $d = 0.84$).
163   CDA was comparable between load-two and load-three conditions ($p = 0.47$, Cohen's d
164     $= 0.13$). However, CDA did not differ between younger and older adults ($F_{1,29} = 1.05$, $p =$
165   0.31, $\eta^2 = 0.029$), nor did we observe an interaction between age and memory load
166   ($F_{2,58} < 1.0$).
167
168   **Alpha Phase Activity Predicts Behavior.** Given the age-related changes in neural
169   activity that we observed, we examined how these changes related to behavioral
170   performance. As noted, older adults performed as well as younger adults on the easiest
171   (load-one and load-two) trials, but performed worse for more difficult load-three trials.
172   We examined the neurophysiological basis for this behavioral aging effect using a
173   multiple linear regression analysis. This analysis allowed us to examine the relative
174   contribution of each neurophysiological measure to behavioral accuracy. Specifically,
175   we modeled d' as a linear combination of cue-evoked alpha ITC, array-evoked alpha
176   amplitude modulation, and delay-period CDA. Cue-evoked ITC was averaged across

177 visual hemispheres, and the lateralized difference was used for array-evoked amplitude
178 activity. Importantly, these physiological measures were indexed during times *prior to*
179 the actual memory challenge and thus are related to trial-by-trial changes in alertness,
180 encoding, or memory maintenance, rather than memory retrieval or response.
181   This model explained 17.1% of the variance in accuracy ($p = 0.045$). Examining
182 the relative contribution of each predictor, we found that after accounting for alpha
183 lateralization and CDA, cue-evoked ITC remained predictive of load-three accuracy ($p =$
184 0.013). Cue-evoked ITC was correlated with load-three accuracy across all participants
185 (Fig. 6a; $N = 31$, Spearman's $r = 0.47$, $p = 0.0071$) and correlated with load-three
186 accuracy across younger adults alone ($N = 17$, Spearman's $r = 0.49$, $p = 0.044$). Alpha
187 lateralization and CDA, on the other hand, did not remain predictive of load-three
188 accuracy after accounting for other physiological measures ($p = 0.28$, $p = 0.94$). Thus,
189 cue-evoked ITC prior to the presentation of to-be-remembered stimuli was a strong
190 predictor of behavioral accuracy, even after adjusting for array-related alpha amplitude
191 and delay-period CDA effects.
192   To further investigate how cue-evoked alpha ITC is associated with behavioral
193 performance, we examined how alpha phase at peak ITC related to subsequent working
194 memory performance. To do so, we determined the timepoint of each participant's peak
195 cue-related ITC, and we pooled all participants' corresponding alpha phases and RTs
196 across trials. During load-three trials in younger adults, alpha phase at peak cue-evoked
197 ITC predicted RTs on a trial-by-trial basis (Fig. 6b, blue; $N = 2499$, $r = 0.14$, $p < 10^{-3}$).
198 Alpha phase at peak cue-evoked ITC also predicted RTs in older adults (Fig. 5B, green;
199 $N = 2090$, $r = 0.079$, $p = 0.0015$). Thus, despite older adults' relatively inconsistent cue-
200 evoked phase response, prestimulus alpha phase was still predictive of load-three RTs.
201 However, the relationship between alpha phase at peak cue-evoked ITC and RT was
202 weaker in older than younger adults ($z = 1.95$, $p = 0.026$).
203
204 **Discussion**
205   In this study, we used a combined visual attention and working memory task to
206 investigate how age-related changes in alertness and spatial attention affect later
207 working memory performance. Using scalp EEG, we found that alpha activity showed
208 age-related alterations during the task, including in older adults' reduced alpha
209 amplitude lateralization during working memory maintenance. In addition, prior to
210 working memory encoding, older participants showed less consistent phase response to
211 a noninformative alerting cue. The consistency of cue-evoked alpha phase reset
212 predicted working memory performance, as did prestimulus alpha phase prior to
213 memory array presentation. Our results provide evidence that alerting cue presentation
214 is accompanied by alpha activity modulation, that neural response to alerting cues is
215 altered during healthy aging, and that the degree of alteration could influence behavioral
216 outcomes.
217   In this task, compared to younger adults, older adults had slower response times
218 in each memory load condition, but lower accuracy only during load-three trials. These
219 slower response times could indicate a speed-accuracy trade-off strategy in older
220 adults, perhaps accounting for older adults performing with accuracy comparable to that

221 of younger adults in low-load conditions. In addition to their longer response times, older
222 adults were less accurate in high-load trials. Thus, any benefit of slowing was unable to
223 preserve performance in high-load trials, underscoring that age-related reductions in
224 attention and working memory performance are more readily apparent during
225 increasingly difficult tasks.
226   Previous research has found that contralateral delay activity (CDA) is related to
227 reduced working memory performance in older frontal and basal ganglia lesion patient
228 populations[21,22]. In this study, we observed no difference in the amplitude or load-
229 dependent modulation of CDA between younger and older adults. A previous study has
230 reported alterations in CDA modulation in older adults[23], but differences between this
231 study and our present study are likely due to our study only presenting stimuli in one
232 visual hemifield at a time. Thus, any age-related differences in the suppression of
233 distractor processing were not tested, likely altering patterns of CDA modulation in older
234 adults.
235   After memory array presentation, alpha amplitude in younger adults diverged
236 between hemispheres, with ipsilateral amplitude higher than contralateral amplitude.
237 Consistent with previous studies[3,4], this alpha lateralization is suggestive of differential
238 processing of the two visual hemifields and the deployment of selective spatial attention
239 in anticipation of the test array, which participants knew would appear in the same
240 visual hemifield as the memory array. This interpretation is also consistent with the lack
241 of alpha lateralization in response to the spatially uninformative alerting cue. Compared
242 to younger adults, older adults showed reduced alpha lateralization, as previously
243 reported in studies with spatial cuing[12,24]. However, neither the degree of alpha
244 lateralization nor the magnitude of CDA predicted older adults' lower accuracy during
245 load-three trials.
246   Instead, cue-evoked alpha phase resetting was less consistent in older adults
247 and was predictive of behavioral performance even after adjusting for array-evoked
248 alpha lateralization and delay-period CDA. Because the alerting cue appeared prior to
249 any stimulus to be encoded in working memory, this result supports findings of reduced
250 alertness in older adults[10,11], with participants' general attentional state being the single
251 best predictor of accuracy more than a second later in the trial. While the age-related
252 inconsistency in cue-evoked alpha phase resetting is opposite that in a previous study[24],
253 this discrepancy could be due to the lack of distractor stimuli and the briefness with
254 which we presented the alerting cue (50 ms). This briefness potentially exacerbated any
255 age-related alterations in cue response, which has not been observed in other
256 studies[5,13].
257   Interestingly, we also found that array-evoked ITC was similar between younger
258 and older adults, despite previous reports showing increased ITC among older adults[24].
259 However, the large, asymmetric cue-evoked ITC differences between younger and older
260 adults may have shifted the ITC baseline, artificially driving up younger-adult ITC. That
261 is, the peak-to-peak difference between cue- and array-evoked ITC is much larger
262 among older, compared to younger, adults. Nevertheless, that cue-evoked alpha phase
263 consistency was predictive of behavioral performance is consistent with previous
264 studies examining alpha phase resetting in response to task-relevant stimuli[25-27]. Our

265   results extend these findings by demonstrating that alpha phase resetting in response to
266   noninformative cues, even prior to presentation of to-be-remembered stimuli, can
267   predict subsequent working memory performance.
268   Alpha phase prior to memory array presentation also predicted response time in
269   high-load trials. This result provides further evidence for the effects of alpha phase on
270   visual working memory[28]. These effects have also been demonstrated in visual
271   detection paradigms[29,30]. Due to the consistent time interval between cue and memory
272   array presentation in our study, it is possible that cue-evoked alpha phase resets led to
273   subsequent memory array presentation at phases facilitative of or detrimental to
274   perception or encoding of the memory array. Older adults' inconsistency in phase
275   response could have led to a greater number of instances in which memory array
276   presentation occurred at suboptimal alpha phases, potentially explaining part of the age-
277   related reductions in performance we observed during high-load trials. However, older
278   adults' weaker relationship between alpha phase and response time suggests age-
279   related reductions in the influence of alpha phase on visual cognition. Physiologically,
280   this reduced influence, as well as older adults' inconsistent cue-evoked phase
281   responses, may relate to age-related increases in neural noise[31,32].
282   Overall, we find that oscillatory alpha dynamics may underlie age-related
283   alterations in attention. Our analysis of alpha phase highlights reductions in older adults'
284   response and attentiveness to alerting cues, with such responsiveness being the
285   strongest predictor of working memory performance. In addition, prestimulus alpha
286   phase predicted performance on a trial-by-trial basis, but less reliably so in older adults.
287   Given that lower performance in older adults can be explained by altered response to
288   alerting cues prior to the task, age-related working memory decline is likely multifaceted
289   and includes alterations in anticipatory attentional allocation as well as in stimulus
290   encoding and maintenance. These findings suggest that changes in neural response,
291   especially in older adults, can occur at multiple timepoints both before and after
292   presentation of task-relevant stimuli, and such alterations likely all have an impact on
293   later cognitive performance.
294
295   **Methods**
296   **Behavioral Task.** Healthy right-handed younger (20-30 year olds, $n = 17$, eight female)
297   and older (60-70 year olds, $n = 14$, seven female) adults with normal or corrected-to-
298   normal vision participated in a visual working memory paradigm. All participants gave
299   informed consent approved by the UC Berkeley Committee on Human Research. In
300   each trial, participants were instructed to maintain central fixation, and at the beginning
301   of each trial, the central fixation cross flashed from gray to pink for 50 ms, alerting
302   participants to the start of the upcoming trial (Fig. 1A). This alerting cue offered no
303   information on either the size or location of upcoming visual stimuli. Three hundred ms
304   after the end of the alerting cue, participants were presented with one, two, or three
305   colored squares for 180 ms in only one visual hemifield. After a 900 ms delay period,
306   during which time no stimuli other than the fixation cross were present, a test array of
307   the same number of squares in the same spatial locations appeared. Participants would

308 manually respond with their right thumb to indicate whether or not the test array had the
309 same color squares as the initial memory array.
310   Behavioral accuracy was assessed using d', a sensitivity measure that takes
311 false alarm and miss rates into account to correct for response bias. To avoid
312 mathematical constraints in the calculation of d', we applied a standard correction
313 procedure in the case of 100% hit rate or 0% false alarm rate. Specifically, hit rate was
314 decreased to 1 - 1/(2N) when necessary, with N being the total number of trials.
315 Similarly, false alarm rate was increased to 1/(2N) when necessary[33].
316
317 **Data Acquisition.** We recorded 64-channel scalp electroencephalography (EEG) from
318 each participant. Participants were tested in a sound-attenuated EEG recording room
319 using a 64+8 channel BioSemi ActiveTwo amplifier (Amsterdam, Netherlands). EEG
320 was amplified (-3 dB at ~819 Hz low-pass, DC coupled), digitized (512 Hz), and stored
321 for offline analysis. Horizontal eye movements (HEOG) were recorded with electrodes at
322 both external canthi. Vertical eye movements (VEOG) were monitored with a left inferior
323 eye electrode and either a superior eye or a fronto-polar electrode. All data was
324 referenced offline to the average potential of two mastoid electrodes and analyzed in
325 MATLAB® (R2015A, Natick, MA) using custom scripts and the EEGLAB toolbox[34].
326
327 **Data Preprocessing.** EEG data was downsampled to 256 Hz and had DC offset
328 removed. EEG data was then highpass filtered above 0.1 Hz using a two-way, fourth-
329 order Butterworth infinite impulse response filter. Any channel whose standard deviation
330 was ±2.5 standard deviations away from the mean standard deviation of all channels
331 was spherically interpolated (on average, 2 channels per participant). Independent
332 component analysis (ICA) was performed using the EEGLAB toolbox, and to remove
333 blink artifacts, ICA components most correlated with the difference between the
334 frontopolar and left inferior eye electrodes were removed.
335   For event-related potential (ERP) analyses and to detect trials with artifacts,
336 continuous EEG data was lowpass filtered below 30 Hz using a two-way, fourth-order
337 Butterworth infinite impulse response filter. Data was epoched around the onset of the
338 memory array using a pre-stimulus baseline of -500 ms to -400 ms. For scalp
339 topographic visualization, and to normalize electrode locations, electrode potentials
340 were swapped right to left across the midline as though stimuli were always presented
341 in the right visual hemifield, making left and right hemisphere channels contralateral and
342 ipsilateral to the stimulus, respectively. Lateralized potentials were analyzed in this
343 ipsilateral-contralateral fashion. Trials where the standard deviation of a scalp electrode
344 exceeded three times the standard deviation of that electrode across all trials were
345 excluded. For saccade trials, trials where the standard deviation of the difference
346 between the HEOG channels exceeded three times the mean of the HEOG channels
347 across all trials were excluded. On average, 69.6% of total trials or 165 trials were kept
348 per participant. No participants were excluded.
349
350 **Data Analysis.** Peak alpha frequency (PAF), the frequency of maximum power
351 between 7 and 14 Hz, varies in a trait-like manner[35] and predicts visual performance[36].

352   To estimate PAF for each participant, we constructed power spectral densities (PSDs)
353   using Welch's method. In order to account for individual differences in $1/f$
354   electrophysiological background, which changes with age[31], we used robust linear
355   regression to estimate and remove the slope and offset of log-log space PSDs prior to
356   identification of PAF.
357   Continuous, non-lowpass-filtered EEG data was bandpass filtered with a 4-Hz
358   passband centered on each participant's PAF. Filters were designed as two-way finite
359   impulse response filters with filter length equal to three cycles of the low cutoff
360   frequency. For each channel, bandpass-filtered time series were converted to z-scores
361   using the mean and standard deviation of artifact-free alpha-band data across all trials
362   and conditions. After normalization, the absolute value and angle of the Hilbert
363   transform of the continuous EEG data was used to extract alpha analytic amplitudes
364   and instantaneous phases, respectively. The phase time series yields cosine phase
365   values of $(-\pi, \pi]$ radians, with π radians corresponding to the trough and zero radians to
366   the peak of the oscillation. This method yields results equivalent to sliding-window fast
367   Fourier transform and wavelet approaches[37].
368   After epoching and removal of marked artifact trials, alpha analytic amplitude
369   time series were subjected to event-related analyses, including the subtraction of
370   baseline activity from -500 ms to -400 ms. To assess trial-to-trial phase consistency
371   (also called intertrial coherence, ITC), event-related phase time series were extracted,
372   and for each time point, the mean vector length of the timepoint's phase distribution was
373   calculated across trials (*circ_r.m* function in the CircStats toolbox[38]). This mean vector
374   length represents the degree of ITC, with ITC of unity reflecting a single adopted phase
375   across trials and a value of zero reflecting uniformly distributed phases across trials. To
376   assess single-subject ITC significance, a resampling approach was used. For each
377   participant, we randomly sampled $n/2$ trials and calculated time-resolved ITC. For each
378   of these sub-samples, we then calculated mean cue/array-related minus mean baseline
379   ITC value. This was done 1000 times to build a single-subject distribution of cue/array-
380   related ITC strength, and H_0 is that the mean of the distribution of differences is zero. A
381   one-sample, one-tailed *t*-test was used to compare the distribution of these differences
382   against H_0 for each participant.
383
384   **Statistical Analyses.** All analyses were performed on data from EEG channels O1/2,
385   PO3/4, and PO7/8, with channels O1, PO3, and PO7 considered contralateral to the
386   memory array. Multiple-factor statistical analyses were assessed via ANOVAs, with age
387   as a between-group factor and memory load and hemisphere as within-group factors.
388   Where sphericity assumptions were violated, degrees of freedom (and hence *p*-values)
389   were adjusted using Greenhouse-Geisser corrections. All single-factor comparisons
390   were analyzed via paired-samples or between-samples *t*-tests. For all alpha ITC
391   analyses except those pertaining to single-subject ITC significance, ITC values were
392   $\log_{10}$-transformed and baseline subtracted. Peak cue- and array-related ITC were
393   assessed using the maximum ITC peak after cue and memory array presentation,
394   respectively. To correlate circular variables like alpha phase with linear variables like

395 response time, a circular-linear correlation was used (*circ_corrcl.m* function in the
396 CircStats toolbox).
397
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505   **Author Contributions**
506   B.V. designed research. S.C.L., L.T., and B.V. performed research. T.T.T. and N.C.H.
507   analyzed the data. T.T.T. and B.V. drafted the manuscript. All authors edited and
508   approved the manuscript.
509

510   **Competing Financial Interests**
511   The authors declare no competing financial interests.
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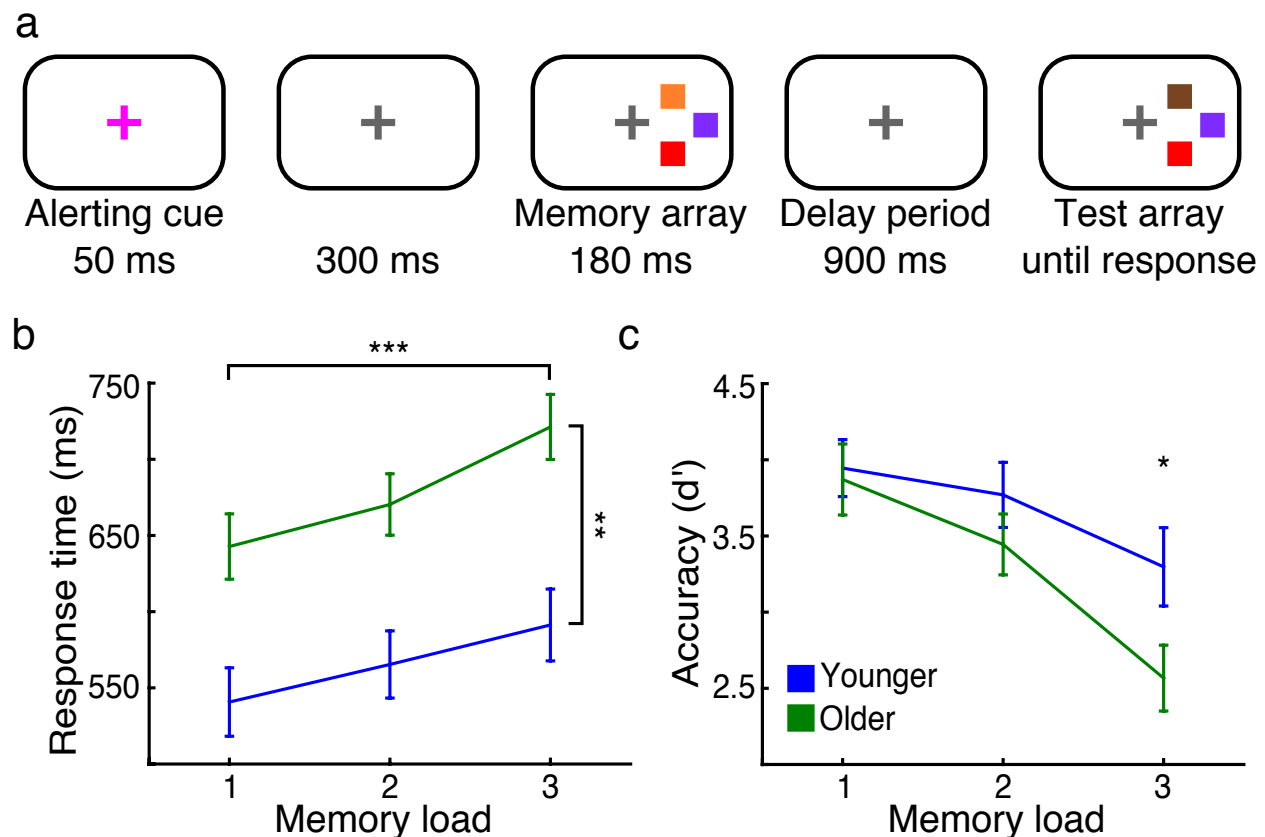
Figure 1. Paradigm, behavioral performance, and event-related activity. (*a*) Diagram of the task design, in this example showing a non-matching test array. (*b*) Response times increased with increasing memory load, with younger adults (blue) faster than older adults (green, ** $p < 0.01$, *** $p < 0.001$; error bars, SEM). (*c*) Accuracy decreased with increasing memory load, with younger adults more accurate than older adults during load-three trials (* $p < 0.05$; age by memory load interaction: $p < 0.01$; error bars, SEM).
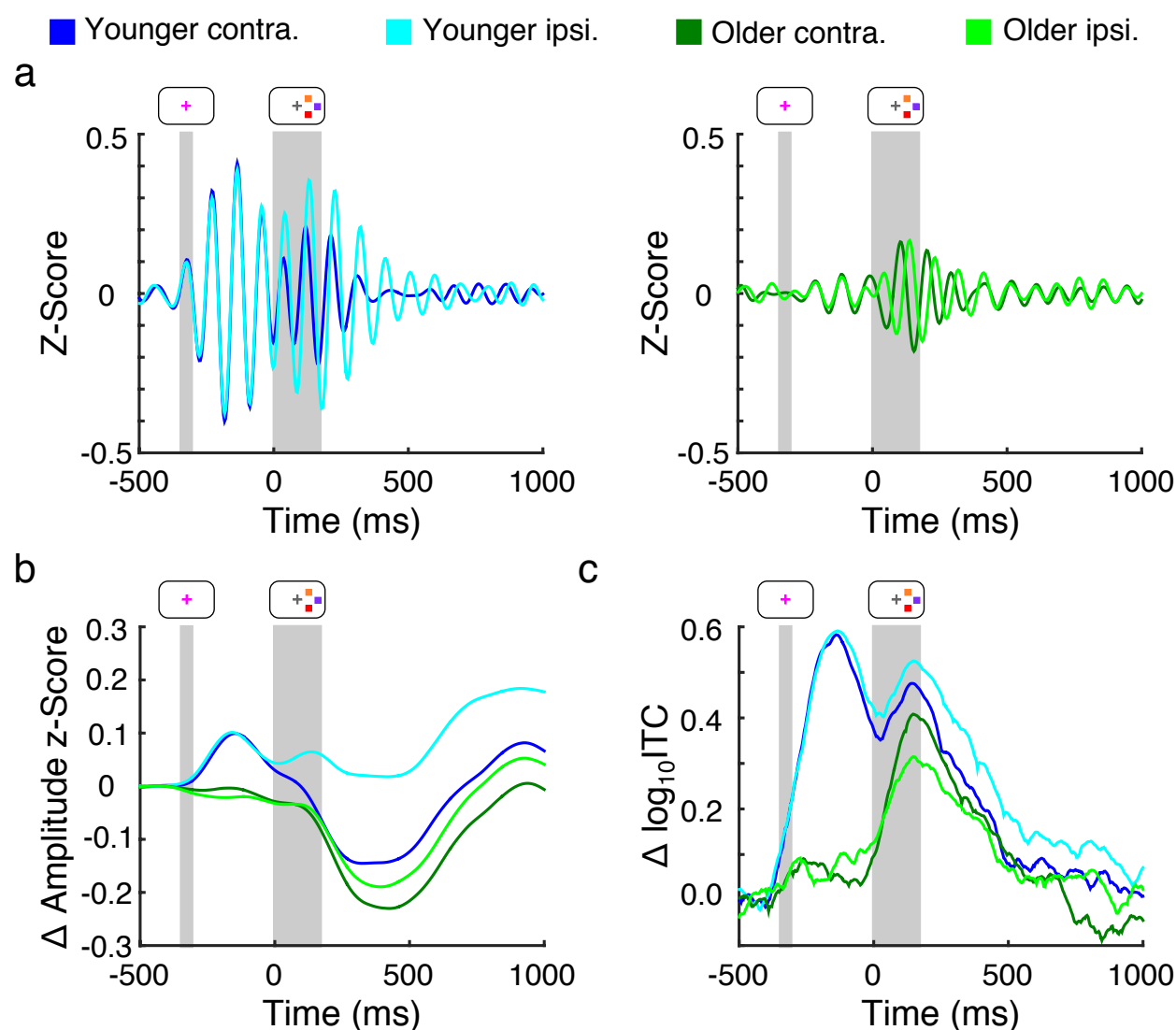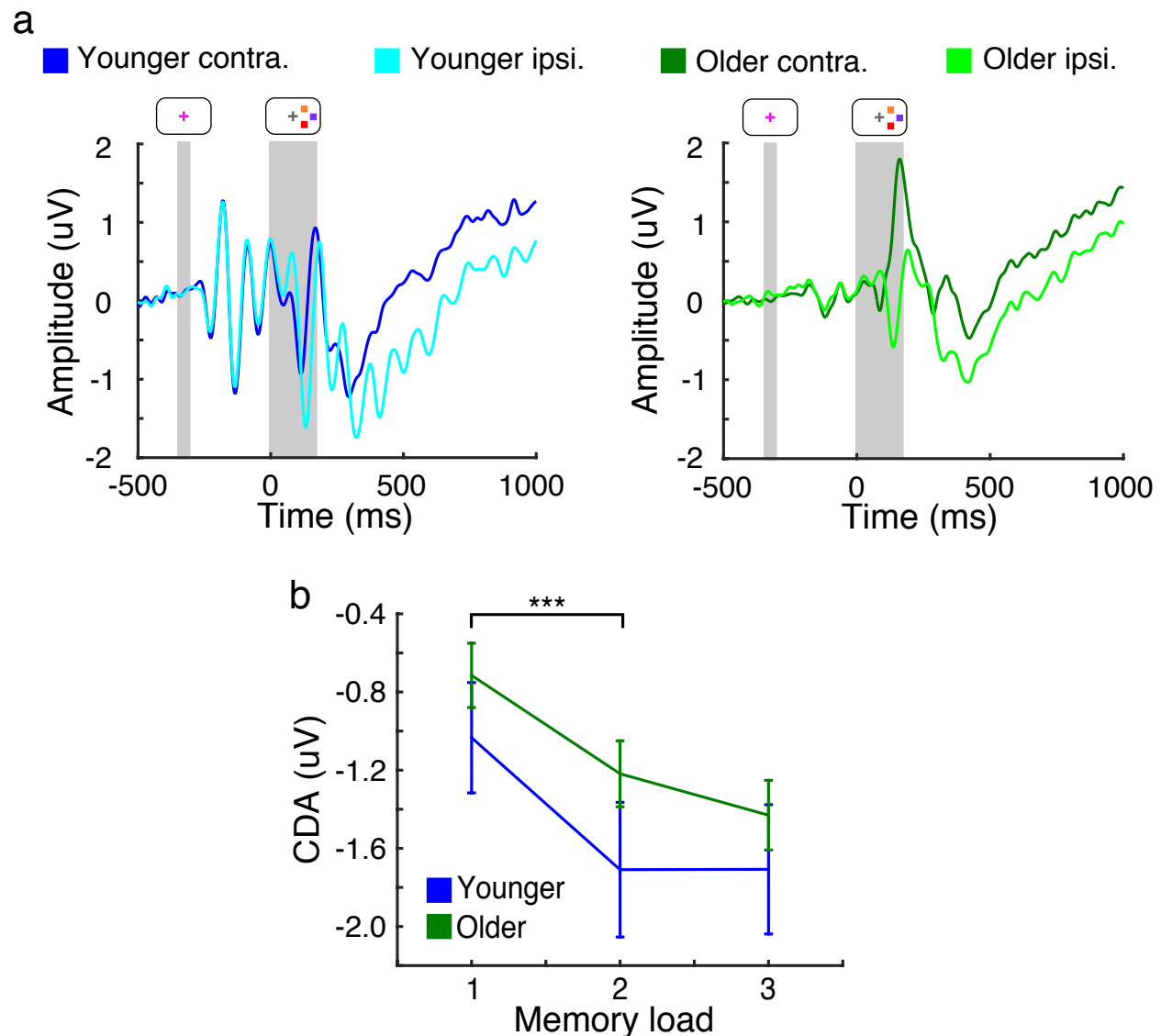
Figure 2. Alpha amplitude and phase activity. a*A*) Grand average visual-area alpha activity contralateral (darker) and ipsilateral (lighter) to the memory array in younger (blue, left panel) and older adults (green, right panel). Gray regions indicate presence and duration of the alerting cue and memory array. Note the hemispheric amplitude differences and strong phase consistency in younger compared to older adults. (*b*) Grand average of changes in visual-area alpha amplitude and (*c*) intertrial coherence relative to baseline, emphasizing the effects observable in (*a*).
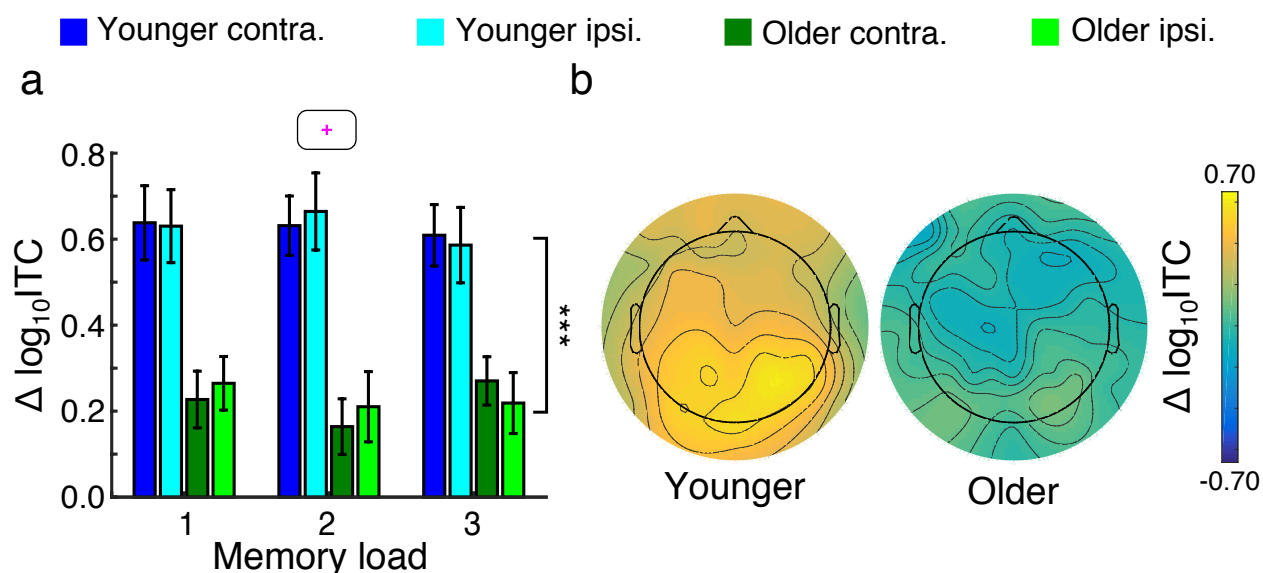
Figure 3. Alerting cue activity. (*a*) Peak alpha intertrial coherence (ITC) in response to the alerting cue. Younger adults (blue) had higher cue-evoked ITC than older adults (green; ***$p < 0.001$; error bars, SEM). (*b*) Topographies of cue-evoked ITC response in younger (left) and older adults (right) during load-three trials.
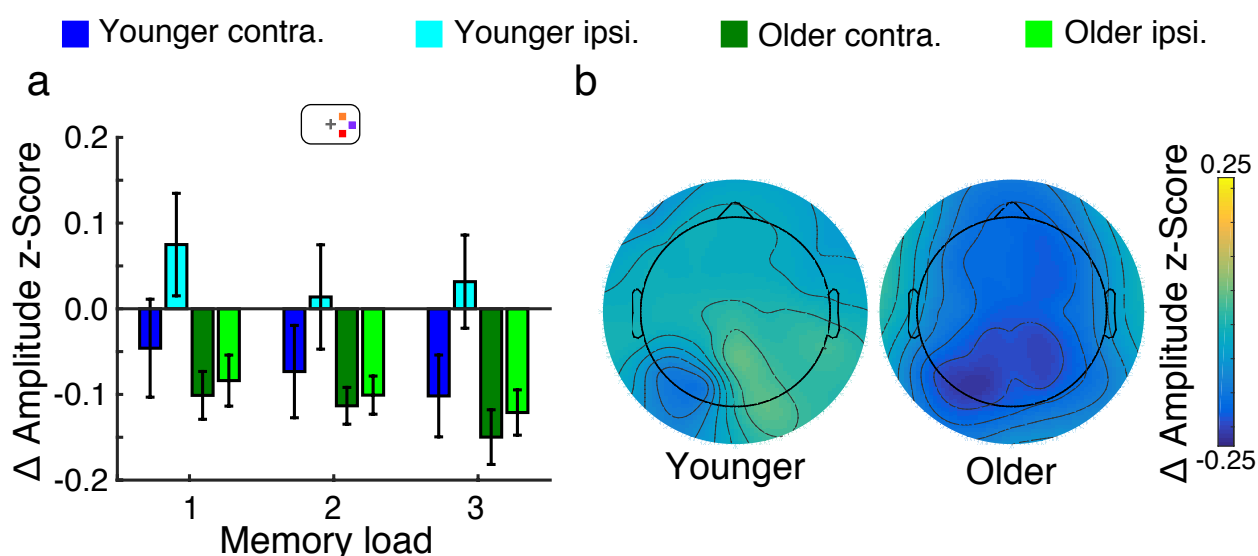
Figure 4. Memory array activity. (*a*) Average change (relative to baseline) in alpha amplitude 0 to 400 ms after memory array presentation. Amplitude decreased from load one to two ($p < 0.05$), and older adults (green) showed decreased alpha lateralization ($p < 0.01$; error bars, SEM). (*b*) Topographies of delay-period alpha amplitude in younger (left) and older adults (right) during load-three trials.

Figure 5. Event-related potential and delay period activity. (*a*) Grand average visual-area activity contralateral (darker) and ipsilateral (lighter) to the memory array in younger (left panel) and older adults (right panel). Gray regions indicate presence and duration of the alerting cue and memory array. Note the sustained negativity in the contralateral hemisphere in both younger and older adults. (*b*) Contralateral delay activity (CDA) increased in magnitude from load-one to load-two conditions, but did not differ between younger and older adults (***$p < 0.001$; error bars, SEM)
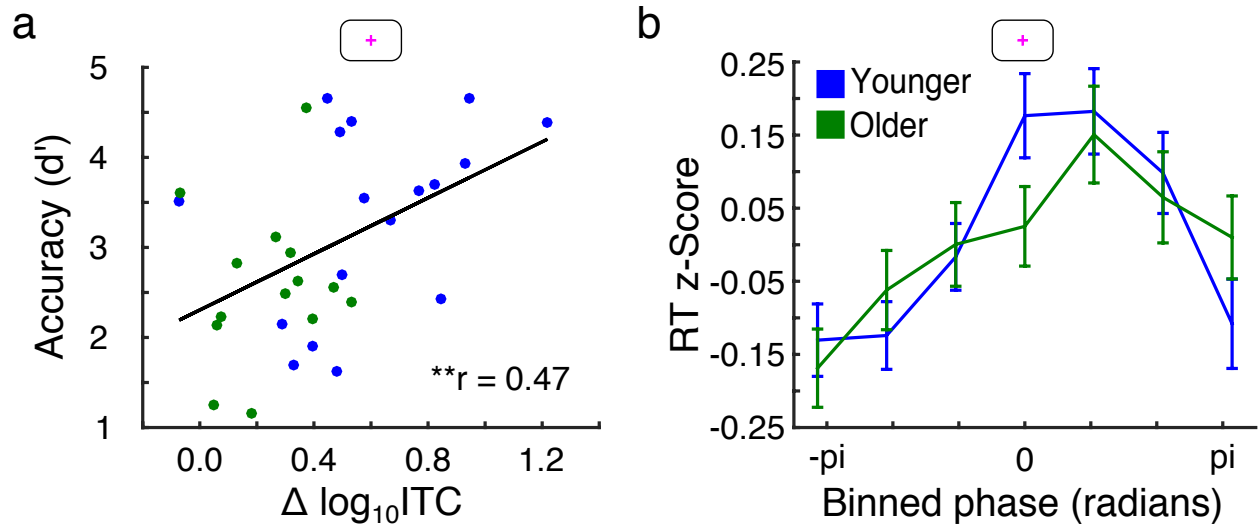
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568 **Figure 6.** Alpha phase predicts working memory performance. (*A*) Cue-evoked alpha
569 intertrial coherence (ITC) versus accuracy during load-three trials across younger (blue)
570 and older adults (green). Cue-evoked ITC was predictive of load-three accuracy (**$p <$
571 0.01). (*B*) Average response time (RT) binned by alpha phase at peak cue-evoked ITC.
572 Phase of zero and ±pi correspond to the peaks and troughs of alpha, respectively. Trial-
573 by-trial alpha phase predicted RTs ($p < 10^{-3}$; error bars, SEM).
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