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Asymmetric Interference Between Cognitive Task Components and Concurrent Sensorimotor
Coordination

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30 Abstract

31 Everyday cognitive tasks are frequently performed under dual-task conditions alongside
32 continuous sensorimotor coordinations (CSC) such as driving, walking, or balancing.
33 Observed interference in these dual-task settings is commonly attributed to demands on
34 executive function or attentional resources, but the time-course and reciprocity of
35 interference are not well understood at the level of information-processing components. Here,
36 we used electrophysiology to study the detailed chronometry of dual-task interference
37 between a visual oddball task and a continuous visuomanual tracking task. The oddball task's
38 electrophysiological components were linked to underlying cognitive processes, and the
39 tracking task served as a proxy for the continuous cycle of state-monitoring and adjustment
40 inherent to CSCs. Dual-tasking interfered with the oddball task's accuracy and attentional
41 processes (attenuated P2 and P3b magnitude, and parietal alpha-band ERD), but errors in
42 tracking due to dual-tasking accrued at a later time-scale, and only in trials in which the target
43 stimulus appeared and its tally had to be incremented. Interference between cognitive tasks
44 and CSCs can be asymmetric in terms of timing as well as affected information-processing
45 components.

46

47 **Keywords:** Dual-tasking, event-related potential, oddball task, tracking, sensorimotor
48 coordination, balancing, walking, gait, driving

49

50 New and Noteworthy

51 Interference between cognitive tasks and continuous sensorimotor coordination (CSC) has
52 been widely reported, but this is the first demonstration that the cognitive operation that is
53 impaired by concurrent CSC may not be the one that impairs the CSC. Also demonstrated is
54 that interference between such tasks can be temporally asymmetrical. The asynchronicity of

55 this interference has significant implications for understanding and mitigating loss of
56 mobility in old age, and for rehabilitation for neurological impairments.

57

58

59

60 There are many instances in everyday human behavior when a continuous sensorimotor
61 coordination (CSC) occurs concurrently with an intermittent cognitive task. CSC tasks are
62 characterized by sustained, task-constrained patterns of body or limb movements generated
63 by a combination of feedforward and perception-based feedback control processes (Seidler et
64 al. 2004). Performance in CSC tasks, such as driving a motor vehicle, goal-directed walking
65 or even upright standing, must be maintained while carrying out a conversation, a sequence
66 of memory or problem-solving operations, or planning future actions. In the case of driving,
67 such dual-task effects have been of particular research interest with respect to interference
68 from mobile (cellular) telephone conversation (Recarte and Nunes 2003; Strayer and
69 Johnston 2001). Dual-task gait and balance have also been extensively researched as
70 concurrent cognitive load is a recognized risk factor in falling in old age (Amboni, Barone
71 and Hausdorff 2013; Rubinstein 2006), and declining dual-task performance is a salient
72 feature not only of healthy aging (Fraizer and Mitra 2008; Springer et al. 2006), but also the
73 time course of neurological conditions such as Parkinson's disease (Bloem et al 2001;
74 Yogev-Seligmann et al 2007) and dementia (Ijmker and Lamothe 2012). Recent research has
75 shown that a range of cognitive tasks interfere with everyday CSCs such as driving (Beede
76 and Cass 2006; Nijboer et al 2016; Recarte and Nunes 2003), walking (Al-Yahya et al. 2011;
77 Holtzer et al 2012) and balancing (Fraizer and Mitra 2008), and that the level of interference
78 tends to be greater in old age (Li and Lindenberger 2002). Thus, despite their apparent
79 autonomy in the healthy young and middle-age adults, everyday CSC tasks make demands on
80 higher level cognitive resources.

81

82 Suggested neuropsychological mechanisms underlying interference during concurrent
83 cognitive operations include attentional capacity-sharing, whereby performance in multiple
84 attention-demanding tasks deteriorates due to limitations in available processing resources

85 (Tombu and Jolicoeur 2003), or as a result of information-processing bottlenecks caused by
86 multiple operations requiring access to a common processor or neural network (Ruthruff et al
87 2001). Multiple resource models (Pashler 1994) have been proposed to explain why
88 interference occurs in certain task combinations (a common resource is accessed) but not in
89 others (the tasks are serviced by separate resources). In the context of CSC-cognitive dual-
90 tasking, the literature on driving (Beede and Kass 2006; Recarte and Nunes 2003; Nijboer et
91 al 2016) and gait (Al-Yahya et al. 2011; Amboni et al 2013) suggests that executive function
92 (EF) operations are the most prone to interference, but research on balancing has been framed
93 in terms of competition for, and allocation of, attentional resources (Redfern et al. 2002;
94 Woollacott and Shumway-Cook 2002). EF broadly refers to higher cognitive processes
95 involved in holding and manipulating task-relevant information in working memory
96 (Baddeley 1996; D'Esposito et al. 1999), and allocating processing resources as required
97 (sometimes termed executive attention) (Baddeley 2007; Norman and Shallice 1986; Royall
98 et al. 2002). In terms of specific information-processing operations, EF includes updating
99 (monitoring and altering WM contents), shifting (switching between task sets) and inhibition
100 of irrelevant information or processes (Miyake et al. 2000; Miyake and Friedman 2012).

101

102 Everyday CSC-cognitive dual-task situations present several challenges in terms of precisely
103 identifying the mechanisms underlying behaviorally observed interference. The first
104 challenge, is that it is generally possible to reduce CSC speed (Haigney et al 2000; Al-Yahya
105 et al. 2011) to enable diversion of information-processing cycles or resources to a concurrent
106 cognitive task. When the CSC exhibits slower speed in the presence of a concurrent cognitive
107 task, it can be unclear whether the interference source was at the level of concurrent
108 attentional resource demands or the EF of switching resources between task sets. A CSC task
109 that does not permit such strategic speed variation could help isolate the effects of common

110 information-processing resource demands.

111

112 The second challenge is that everyday CSCs have a degree of performance tolerance that can
113 be exploited to fit in the demands of a concurrent cognitive task. For example, highway lane
114 width and walking paths allow a level of trajectory deviation without compromising safety or
115 overall task goals (Nijboer et al. 2016; Springer et al. 2006). It is usually possible to
116 strategically allow a level of error to accumulate in order to fit in the demands of a secondary
117 task. A CSC task that isolates the use of perceptual information to continuously stabilize the
118 coordination (i.e., exposes all deviations as error) could help locate the precise loci of
119 interference between processes of CSC maintenance and the operations of a concurrent
120 cognitive task.

121

122 The third challenge in understanding CSC-cognitive dual-task interference is that most
123 everyday cognitive tasks involve perceptual, attentional and executive function sub-
124 processes. Interference between such tasks and CSCs may affect one or more of these sub-
125 processes, and the effects may or may not be symmetrical. Behavioral measures such as
126 accuracy or response time in cognitive tasks, and the variability of lane deviation, stride
127 length or body sway, cannot by themselves resolve the chronometric details of these
128 interactions as they reflect the cumulative effects of the tasks' central and response-related
129 information-processing components. If the sequence of neurophysiological events associated
130 with the sub-processes of a cognitive task are known and observable, investigating these
131 events' interactions with a CSC stabilization task could provide a more detailed
132 understanding of the structure and timing of CSC-cognitive interference.

133

134 Here, we addressed these challenges by asking participants to perform a visuomanual pursuit-

135 tracking task (Chernikoff et al. 1955), and used electrophysiological techniques to investigate
136 the chronometric details of this CSC's interactions with the extensively studied cortical
137 dynamics of the visual oddball task (Fig. 1). The key interest in this task combination was
138 that the timing and reciprocity of influence from either task to the other could be studied at
139 the level of component processes. It is seldom clarified whether, for example, the attentional
140 component of a cognitive task that is disrupted by a concurrent CSC is also the cognitive task
141 component that disrupts CSC performance. Addressing the outlined challenges and utilizing
142 the high temporal resolution of electrophysiological events enables the present study to detect
143 possible asymmetries in interference at the level of task components.

144

145 Pursuit-tracking has a long history of use in studies of dual-task interference (e.g., Brown
146 1998; Gazes et al. 2010; Isreal et al 1980; Kramer et al 1983;), including as a simulated
147 driving task (e.g., Strayer and Johnston, 2001), and as a secondary task during postural
148 perturbations (e.g., McIlroy et al. 1999; Norrie et al. 2002). In the laboratory, pursuit-tracking
149 involves continuously minimizing the positional error between a manually controlled cursor
150 and an independently moving, computer-controlled visual target on a screen (Brown 1998;
151 Gazes et al. 2010). Our use of pursuit-tracking addressed the first two challenges identified
152 above by enforcing the maintenance of CSC speed, and allowing no strategic trajectory
153 deviation or variability without accumulating detectable horizontal and vertical positional
154 errors.

155

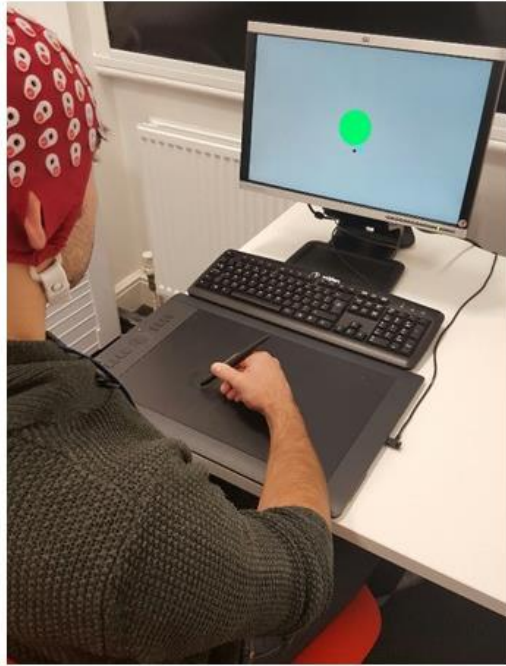
156 To address the issue of sub-processes, we incorporated a visual oddball task as the concurrent
157 cognitive task. The oddball task required an action only when the less frequent of two
158 possible stimuli was detected (Hillyard et al. 1973). The template for the target stimulus had
159 to be maintained in WM and matched to the current perceptual stimulus. This involved top-

160 down facilitation of matching features and inhibition of non-matching ones (D'Esposito and
161 Postle 2015). As a physical response (such as clicking a button or pressing a foot pedal) could
162 introduce an additional motor interference, the participants instead produced a cognitive
163 response—mentally tallying the number of targets detected over the current block of trials.
164 This covert-response variant of the oddball task has an electrophysiological signature
165 analogous to that of the overt, motor-response version in the stimulus processing phase (Potts
166 2004; Salisbury et al. 2001; Verleger et al. 2016), but it also involves an additional WM
167 component of maintaining the current target count, and an executive function of updating
168 (Garavan et al. 2000) the tally every time a target is identified (Fig. 1).

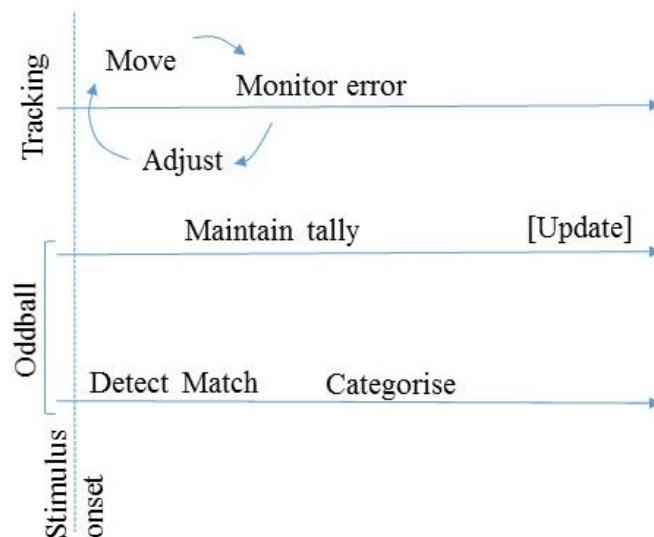
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FIGURE 1

a.



b.



170

171

172 The oddball task is well suited to studying dual-task interference at the level of information-
 173 processing components because extensive research has linked its electrophysiological
 174 correlates to the time course of its underlying cortical processes (Polich 2007). We consider
 175 event-related potentials (ERP) first, followed by spectral characteristics of EEG data. Three
 176 event-related potential (ERP) components express the key features of information processing
 177 in this task. P1 occurs around 100 ms post-stimulus-onset over occipital sites, and is sensitive

178 to bottom-up stimulus characteristics such as brightness or contrast (Johannes et al. 1995). P2
179 occurs anteriorly about 200 ms post-stimulus-onset, and is thought to represent top-down
180 mechanisms by which the current stimulus is compared to representations of previous ones
181 (e.g., known templates for standard and target stimuli) (Kim et al. 2008; Luck 2005). The P3b
182 occurs 300-400 ms post-stimulus-onset and is thought to correspond to stimulus
183 categorization (that it is a target), and acknowledgement of task relevance (that the tally
184 requires updating) (Polich 2007; Luck 2014). Previous research suggests that, if concurrently
185 performing the tracking task impedes only the top-down aspects of oddball task performance,
186 only P2 and P3b, but not P1, will be attenuated (Allison and Polich 2008; Isreal et al. 1980;
187 Kida et al. 2004; Matthews et al. 2006). In this study, we used target stimuli (shaded circles)
188 with greater contrast than the standard stimuli (unshaded circles), such that a bottom-up
189 stimulus effect might be expected for P1 (Johannes et al. 1995), but not a dual-task effect,
190 unless the tracking task also degraded the bottom-up perceptual processing of the oddball
191 stimulus.

192

193 The oscillatory characteristics of cortical networks underpinning oddball task performance
194 can be examined through event-related spectral perturbations of EEG recorded from parietal
195 and frontal sites (Makeig et al. 2004). At parietal sites, an event-related desynchronization
196 (ERD) in the alpha band (8-13 Hz) occurs approximately 400-600 ms post-stimulus-onset
197 when a change in processing is required, such as when the rarer target as opposed to the
198 standard stimulus appears (Sutoh et al. 2000). If the detection of this change is impaired by
199 dual-tasking, parietal ERD ought to be attenuated. Also, a larger alpha-band response to a
200 target as opposed to a standard stimulus is known to occur at anterior locations at these
201 latencies (Yordanova and Kolev 1998; Başar and Güntekin 2012). Alpha power at fronto-
202 central sites in tasks involving WM processes is thought to reflect inhibition of task-irrelevant

203 information (Klimesch et al. 1998). However, recent work using post-cuing paradigms, that
204 allow systematic manipulation of relevant and irrelevant WM load (Manza et al. 2014),
205 suggest that fronto-central alpha power reflects maintenance of task-relevant WM load, and is
206 related to task accuracy. Either way, if dual-tasking added to WM load, then an increase in
207 frontal alpha power (alongside lowered accuracy) would be expected.

208

209 Coordination in the fronto-parietal network (Corbetta and Shulman 2002) underpinning
210 attention and WM tasks (such as oddball detection) is electrophysiologically reflected in
211 alpha-band coherence between frontal and parietal sites (Sauseng et al. 2006; Güntekin and
212 Başar 2010; Sadaghiani et al. 2012; van Schouwenburg et al. 2017). Güntekin et al (2008)
213 have shown, for example, that impaired cortical connectivity in Alzheimer's reduces fronto-
214 parietal alpha-band coherence in a visual oddball task. If concurrently performing
215 visuomanual tracking reduces the effectiveness of the fronto-parietal network, a lower level
216 of alpha coherence would be expected.

217

218 Turning to the effects of the oddball task on pursuit-tracking, if the oddball task reduces
219 motor programming resources for pursuit-tracking, we might observe differences in spectral
220 power over contralateral motor cortex relative to the tracking-only condition. Manual task
221 execution is accompanied by an event-related desynchronization (ERD) over contralateral
222 primary motor cortex characterized by reduced power in the alpha (7-13 Hz) and beta (13-30
223 Hz) bands (Pfurtscheller and Lopes da Silva 1999). If concurrent performance of the oddball
224 task reduces resourcing of the tracking task, we would expect reduced ERD (i.e., higher
225 spectral power) over contralateral motor cortex during dual-tasking relative to performing
226 tracking by itself.

227

228 In terms of tracking performance, any disruption resulting from the concurrent oddball task
229 would be detectable as vertical and horizontal positional deviations from the set trajectory.
230 More importantly, the timing of such deviations would be highly informative in time-locked
231 juxtaposition with the electrophysiological indicators of the oddball task's cortical processes
232 (see Fig. 1). Positional error accruing in the P2 timescale would be indicative of a top-down
233 attentional process in a concurrent cognitive task that disrupts tracking. Deviation in the P3b
234 timescale would implicate the processes of task-relevance judgement. If error build-up occurs
235 later still, then the executive function of updating (incrementing the target count) would be
236 the most likely interference source.

237

238 In summary, we hypothesized that performing the tracking task concurrently with the oddball
239 task would not affect the oddball task at the P1 timescale, but would attenuate P2 and P3
240 amplitudes, indicating reduced attentional resourcing of oddball task performance. We also
241 expected that dual-tasking would attenuate parietal alpha-band ERD, indicating impaired
242 target detection in the oddball task. Further, we expected an increase in frontal alpha power
243 (and lower accuracy) in the dual-task target condition, confirming an overall increase in WM
244 load in that condition. Also, we expected to see reduced fronto-parietal alpha-band coherence
245 in the dual-task condition as an indication of degraded resourcing in the dual-task condition.

246

247 The above hypotheses were derived from the expectation that the concurrent tracking task
248 would impede resourcing of the oddball task. In the reverse direction, if the cognitive task
249 load interfered with tracking, we expected to see positional errors develop at the time periods
250 of this interference. Also, if the concurrent oddball task negatively impacted resourcing of the
251 tracking task, we expected to observe weaker ERD over contralateral motor cortex in the
252 dual-task condition.

253

254 The key interest in this work lies in the symmetry and synchrony of the expected
255 interference. If the component of the oddball task that had a negative impact on tracking was
256 also the task component that was impaired by tracking, we would have expected these
257 reciprocal effects to be synchronous. On the other hand, if, say, tracking affected the
258 attentional components of the oddball task, but it was the later executive function component
259 of the oddball task that impaired tracking, then we would have expected to see temporally
260 separated directional effects on electrophysiological components and task performance.

261

262 **Materials and Methods**

263 *Participants*

264 The participants were 24 self-reportedly right-handed adults (13 females; mean age = 25.6
265 years, $SD=6.13$, range 19-42), with normal or corrected to normal vision, no current
266 prescribed medication, and no history of sensorimotor or cognitive deficits. They were
267 recruited through a research participation scheme for students, and given research credits in
268 return for their participation. The participants gave informed consent before the session, and
269 were fully debriefed at the end. Ethical approval for the research reported in this paper was
270 granted by the Nottingham Trent University College of Business, Law and Social Sciences
271 Research Ethics Committee.

272

273 *Apparatus and Experimental Procedure*

274 The participants sat in a comfortable and stable chair with their eyes positioned
275 approximately 60 cm from the center of a 19" (48.26 cm) diagonal color LCD screen
276 displaying 1600 x 900 pixels at 60 Hz (Fig. 1a). After explaining the required tasks and the
277 structure of the session, the experimenter obtained written informed consent, and then

278 administered a motor configuration task to establish the participants' comfortable
279 visuomanual tracking speed. The participant was then prepared for EEG data recording using
280 a 128-channel ActiveTwo Biosemi system (Amsterdam, The Netherlands). Electrodes were
281 placed in the Biosemi ABC configuration using an elastic cap fitted to the participant's head.
282 The participant then performed the visuomanual tracking, visual oddball and dual-task
283 sessions. To prevent practice and fatigue factors from affecting differences between these
284 three task conditions, the order of these sessions was counterbalanced across participants.
285 Participants were instructed to fixate at the center of the display (fixation cross) at all times
286 for each of the task conditions and to avoid looking at the moving dot and cursor.

287

288 *Motor task configuration*

289 With eyes fixated at the center of the screen, the participants used a Wacom Intuos Pro
290 digitizing tablet and stylus (Saitama, Japan) to pursue a small cyan-colored leading dot ($r =$
291 25 pixels) rotating clockwise in a circle ($r = 130$ pixels; 36 mm) around a fixation cross (see
292 Figure 1a). Participants were positioned so that their eyes were approximately 800-850 mm
293 from the fixation cross on the screen, so the leading dot's track subtended a visual angle of
294 2.42° - 2.57° with eyes at fixation. Note that the ability to split covert attention between spatial
295 locations has been tested at up to 3.5° of eccentricity from fixation (e.g., McMains and
296 Somers 2004). The stylus' position was represented on screen as a black dot ($r = 20$ pixels),
297 and the participant's task was to move the stylus over the tablet so as to keep the black,
298 controlled dot overlaid on the leading cyan dot throughout the trial duration (10 s). Seven
299 trials were presented sequentially in which the angular velocity of the leading dot increased
300 from 84 degrees per second (dps) in the first trial to 168 dps in the seventh trial (in 12 dps
301 increments). The same seven trials were then presented in reverse order. For each trial, the
302 proportion of the final 7 seconds of trial time during which the two dots overlapped in

303 horizontal (x) and vertical (y) coordinates was calculated. The angular velocity at which a
304 participant produced their third best tracking performance was taken as that participant's
305 comfortable visuomanual tracking speed. The participants' chosen velocities ranged from 96
306 dps to 144 dps. The most common comfortable speed was 120 dps.

307

308 *Visuomanual tracking task*

309 The participants performed the visuomanual tracking task at their comfortable speed (as
310 determined earlier by the configuration task). This part of the session consisted of 8 blocks,
311 each lasting 120 s. The screen coordinates of the leading and controlled dots, and the
312 participants' EEG data were recorded.

313

314 *Visual oddball task*

315 The participants fixated at the center of the screen while a sequence of shaded (target) or non-
316 shaded (standard) circles ($r = 100$ pixels) were presented, centered on the fixation cross (Fig.
317 1a). These stimuli were presented for 200 ms, with an ISI of 2500 ms (Fig. 1b). The ratio of
318 target to standard stimuli was 1:4, and there were at most 12 targets presented in each block
319 (the number of trials per block varied between 40 and 60). The participants' task was to
320 silently count up the number of targets presented in a block, and report it via the keyboard
321 once the block had finished. There were 8 blocks of trials in total and the number of blocks in
322 which the number of targets were counted correctly was recorded, as were the participants'
323 EEG data. Accordingly, accuracy on the oddball task was recorded as either a 1 (accurately
324 reported the number of targets in the block), or 0 (did not report the correct number of targets
325 in the block), for each of the 8 blocks.

326

327

328 *Dual-tasking*

329 The participants performed the visual oddball task whilst also performing the visuomanual
330 tracking task. Each block of trials started with the leading and controlled dots in an
331 overlapping position. As the leading dot started moving, and the oddball task got under way,
332 the participants' task was to maintain the positional overlap between the dots while
333 performing the oddball task. The coordinates of the controlled and leading dots, the target
334 count and the EEG data were recorded. As in the single-task conditions, the instruction
335 throughout was to maintain eye fixation on the cross at the center of the screen.

336

337 **Experimental Measures and Analyses**

338

339 *Oddball detection performance*

340 Performance on the oddball task was taken as the proportion of blocks in which participants
341 correctly counted all of the target stimuli presented. Accuracy on a given block was reported
342 as either a 1 (correctly reported the number of targets presented), or a 0 (incorrectly reported
343 the number of targets). Overall oddball task performance for each participant for each
344 condition (single and dual task) was calculated as a percentage of correct blocks out of all of
345 the possible 8 blocks.

346

347 *Visuomanual tracking deviation analysis*

348 The instantaneous positional discrepancy (in pixels) between the leading and controlled dots
349 in the visuomanual tracking task was calculated as horizontal (X) and vertical (Y) deviation.
350 For each frame, the quadrant in which the lead dot was located was used to calculate the sign
351 of the deviation such that it would always have a negative value when the controlled dot
352 trailed the lead dot, and vice versa (e.g., $\text{deviation}(X) = \text{controlled}(X) - \text{lead}(X)$ in quadrants

353 I and IV, but $\text{deviation}(X) = \text{lead}(X) - \text{controlled}(X)$ in quadrants II and III). Deviation in the
354 vertical axis was also calculated using analogous arithmetic. Deviation samples were epoched
355 around the oddball stimulus onset (-150 to 1500 ms). In the condition with only the
356 visuomanual tracking task, deviation samples were epoched using the visual oddball task's
357 timeline just as in the case of the dual-task condition, except that the oddball task stimuli
358 were not displayed.

359

360 *EEG data acquisition*

361 EEG data were acquired using 128 Ag/AgCl active pin electrodes at 2048 Hz and digitised
362 with 24-bit resolution. Data were referenced online using a CMS/DRL feedback loop with
363 online low pass filtering performed in the Analogue-Digital-Converter (5th order sinc
364 response with a -3 dB point at 1/5th of the sampling rate). Electrode offsets (difference in μV
365 of each channel from CMS electrode) were examined after electrode application and
366 addressed if the absolute value was $>20\mu\text{V}$. Digital markers (event codes) were inserted into
367 the continuous EEG via a DB25 cable through a USB-Parallel port interface (Neurospec AG,
368 Switzerland).

369

370 *EEG data pre-processing and epoching*

371 Continuous EEG data were imported and processed in bespoke scripts using functions from
372 EEGLAB (Delorme and Makeig 2004). Data were down sampled to 256Hz, high-pass
373 filtered at 1 Hz and low-pass filtered at 50Hz using a linear finite impulse response filter.
374 Line noise (50Hz and 100Hz harmonic) was estimated and removed from each channel using
375 CleanLine (Mullen 2012). Linear trends were removed from the data by removing the mean
376 of each channel. Noisy channels were identified from datasets by visual inspection for
377 residual high frequencies and extreme values and then eliminated. Channels with kurtosis

378 over 5 SD from the mean kurtosis of all channels were also removed. EEG epochs were
379 generated by extracting data for -150 to 1500 ms around each event (oddball stimulus onset).
380 EEG epochs were manually searched for artefacts and were removed if they were considered
381 to contain low frequency drifts and/or high frequency activity considered to be
382 biomechanical. EEG was finally re-referenced to an average of all channels followed by the
383 removal of one channel (D32) from each dataset. Re-referencing to an average of all channels
384 reduces the data rank to $n-1$ and can produce artefactual/duplicate independent components.
385 Removing one (D32) channel corrected for this.

386

387 *Independent components analyses for artefact rejection*

388 Independent Components Analysis (Infomax ICA;(Bell and Sejnowski 1995)) was applied to
389 EEG epochs to identify neural components contributing to the observed scalp data. ICA
390 involves the linear de-mixing of signals measured across the scalp and is able to separate out
391 and identify electrical sources that are maximally temporally independent, thus allowing the
392 analyses of neural functions in source space (as opposed to sensor space). Component
393 properties (time-series, spectra, topography) were explored in order to identify ocular and
394 muscle components. Ocular components such as blinks and lateral eye movements were
395 identified by low-frequency, non-time-locked fluctuations in the EEG epochs with strong
396 power toward the front of the scalp. Muscle components were identified by high frequency
397 activity in the EEG epochs with concentrated activity close to the jaw. Any suspect ocular
398 and muscular components identified as artefactual during this process were removed from the
399 EEG data structure, thus removing their contributions to the observed EEG.

400

401

402

403 *Event-related potential (ERP) analyses*

404 The EEG epochs were baseline-corrected by removing the mean of a baseline period (-150
405 ms to stimulus onset) from the entire epoch. A series of frames displaying grand average
406 voltage distribution over the scalp was produced from 0 to 1000 ms post stimulus-onset in 5
407 ms intervals for each condition. These frames were stitched together to produce an animation
408 of scalp topography. The locations of maximum voltage in the time-range 80-120 ms, 180-
409 220 ms, and 380-420 ms were used to determine electrode clusters for the extraction of
410 component measurements. A virtual electrode approach (Foxe and Simpson 2002; Rousselet
411 et al. 2010) was used to generate ERPs consisting of the maximum value over a cluster of
412 electrodes at each time point throughout the epoch. This approach accounts for individual
413 differences in which electrodes respond maximally to task stimuli (Rousselet et al., 2010).

414

415 Difference wave ERPs for each participant were generated by subtracting the standard
416 stimulus response from the target stimulus response for both single and dual task conditions.
417 This resulted in waveforms representing the difference in target and standard stimulus
418 processing. P1 amplitude was quantified as the maximum difference (μV) within the 80-120
419 ms post stimulus period across a right occipital electrode cluster containing B7, B8, B9, A26,
420 A27 and A28 electrodes. P2 amplitude was quantified as the maximum difference (μV) within
421 the 180-220 ms post stimulus period across a midline fronto-central electrode cluster
422 containing C26, C20, C13, C25, C21 and C12 electrodes. P3b amplitude was quantified as
423 the maximum difference (μV) within the 300-500 ms post stimulus period across a midline
424 parietal cluster containing A5, A19, A32, A18, A20 and A31 electrodes. P1, P2, and P3b
425 latency were taken as the times (ms) of the respective maximum differences.

426

427

428 *Time-frequency representation and cross-channel coherence of EEG waveforms*

429 The newtimef function in EEGLAB (Delorme and Makeig 2004) was used to carry out zero-
430 padded FFTs with hanning window tapering to estimate the spectral composition of the EEG
431 signal. For each participant, a time-frequency matrix was produced containing log power
432 (dB) values of 100 frequencies in the 3-45 Hz range over the -150-1500 ms period of each
433 epoch. Average log power values in the 7-13 Hz were taken as alpha-band power. Cross-
434 channel coherence was used to quantify the instantaneous coupling of the amplitude and
435 phase of alpha oscillations between frontal (C21) and parietal (A19) sites. Coherence
436 matrices for both amplitude and phase were generated for each participant, giving a
437 coherence coefficient for each frequency at each time point.

438

439 *Spectral power over motor cortex*

440 The spectopo function in EEGLAB was used to derive alpha and beta power spectral density
441 at left hemisphere (D19) and right hemisphere (B22) sites (corresponding to C3 and C4,
442 respectively, in the International 10-20 system) during single-task and dual-task standard and
443 target (oddball task) trial periods, and during the single-task motor-only trial periods. Also,
444 alpha and beta power in the dual-task standard and target, and single-task motor task
445 conditions was calculated for six time bins (0-200, 200-400, 400-600, 600-800, 800-1000,
446 and 1000-200 ms) to test for any power differences that may have occurred over shorter
447 durations and therefore could not be detected across whole trial periods.

448

449 **Results**450 *Oddball target detection accuracy*

451 A paired-samples t-test using an empirical logistic transformation ($c=0.001$) was conducted
452 to compare target detection accuracy (%) in both single and dual-task conditions. Accuracy

453 was greater in the single ($M=72.17$, $SD=16.65$) than dual-task condition ($M=48.21$,
454 $SD=20.39$); $t(23)= 2.81$, $p<.001$. $M1-M2$ (back-transformed) = 0.78, CI [0.58 0.91].

455

456 *ERP components*

457 The effects of dual-tasking on the amplitude and latency of P1, P2 and P3b difference waves
458 were analysed using paired sample t-tests (Figs. 2, 3). The P1 difference wave's amplitude
459 did not differ between single and dual task conditions ($t(23) = 1.36$, $p=.19$), but P2 ($t(23) =$
460 4.02 , $p<.001$) and P3 ($t(23) = 4.03$, $p<.001$) difference waves' amplitudes were smaller
461 during dual tasking. As standard and target stimuli (unfilled and filled circles, respectively)
462 differed in bottom-up stimulus characteristics such as brightness and contrast, a stimulus
463 effect on P1 was expected regardless of task conditions. P1 amplitude was indeed greater for
464 target than standard stimuli under both single-task ($t(23) = 7.58$, $p<.001$) and dual-task ($t(23)$
465 $= 4.43$, $p<.001$) conditions.

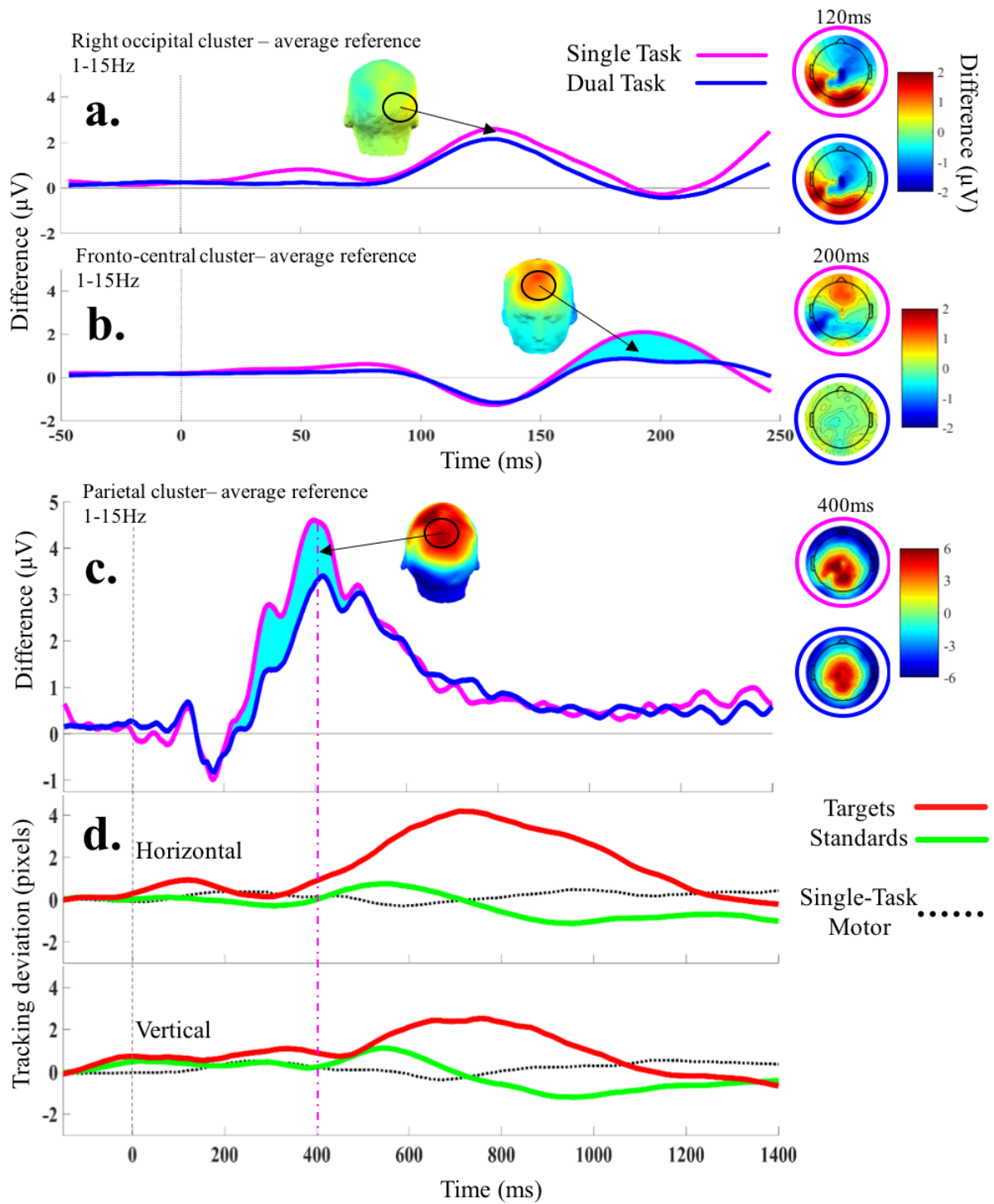
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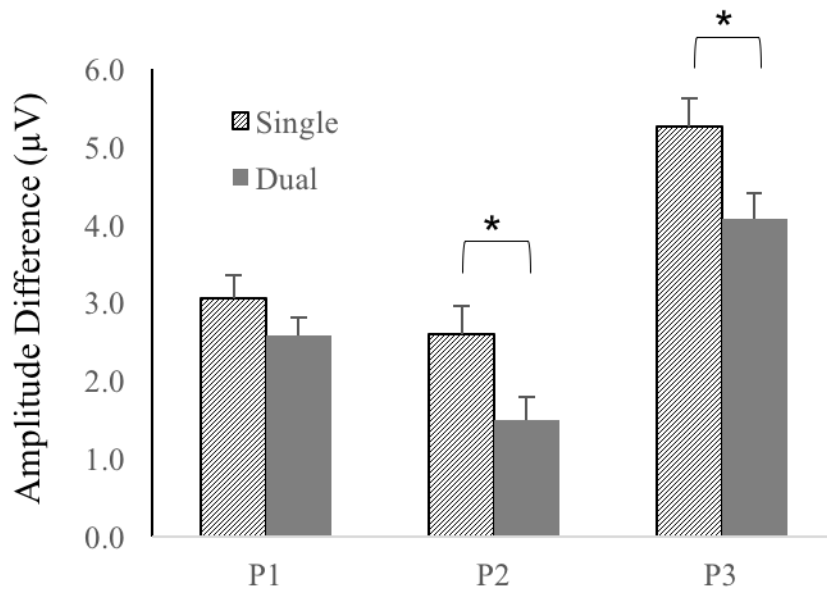
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FIGURE 2



470

471 **FIGURE 3**

472

473

474 *Relationship between P2 and P3b amplitude and tracking speed*

475 As participants differed in their preferred tracking speed (speed ranged from 96 to 144 dps),
 476 we tested whether participants' P2 and P3b components have been affected by the value of
 477 tracking speed. Neither P2 ($r=.06, p=.77$) nor P3b amplitude ($r=-.07, p=.77$) was significantly
 478 correlated with tracking speed.

479

480 Spectral characteristics of EEG and visuomanual tracking deviation data were analyzed using
 481 repeated measures ANOVA with the significance level for omnibus effects set to $p<.05$. A
 482 Bonferroni correction was applied ($.05/n$; n = number of mean comparisons) to post hoc tests
 483 using Fisher's LSD. Generalized eta square (η^2) (Olejnik and Algina 2003) was used as the
 484 effect size statistic.

485

486

487

488 *Parietal and frontal alpha-band power and fronto-parietal alpha-band coherence.*

489 Experimental effects on parietal and frontal alpha-band power, and fronto-parietal alpha-band
490 amplitude and phase coherence were analysed using a 2 (Task: single, dual) x 2 (Stimulus:
491 standard, target) x 20 (time) repeated measures ANOVA. Time bins were of 50 ms duration
492 and spanned 0-1000 ms post stimulus onset. Frontal alpha-band power was analysed over the
493 550-1000 ms time period (as previously discussed).

494

495 *Parietal alpha-band power*

496 On parietal alpha-band power, there were significant main effects of task ($F(1, 23) = 4.75$,
497 $p < .05$, $\eta_G^2 = .031$), stimulus ($F(1, 23) = 70.13$, $p < .01$, $\eta_G^2 = .021$), and time ($F(19, 437) =$
498 20.62 , $p < .001$, $\eta_G^2 = .132$), and significant task x stimulus ($F(1, 23) = 6.04$, $p < .05$, $\eta_G^2 = .010$),
499 task x time ($F(19, 437) = 3.48$, $p < .001$, $\eta_G^2 = .013$), stimulus x time ($F(19, 437) = 12.51$,
500 $p < .001$, $\eta_G^2 = .038$), and task x stimulus x time ($F(19, 437) = 5.97$, $p < .001$, $\eta_G^2 = .011$)
501 interactions. As shown in Figs. 4 and 5, the desynchronization in the 450-650 ms period that
502 was observed for target stimuli in the single task was attenuated in the dual task. There was
503 no corresponding pattern in the case of standard stimuli.

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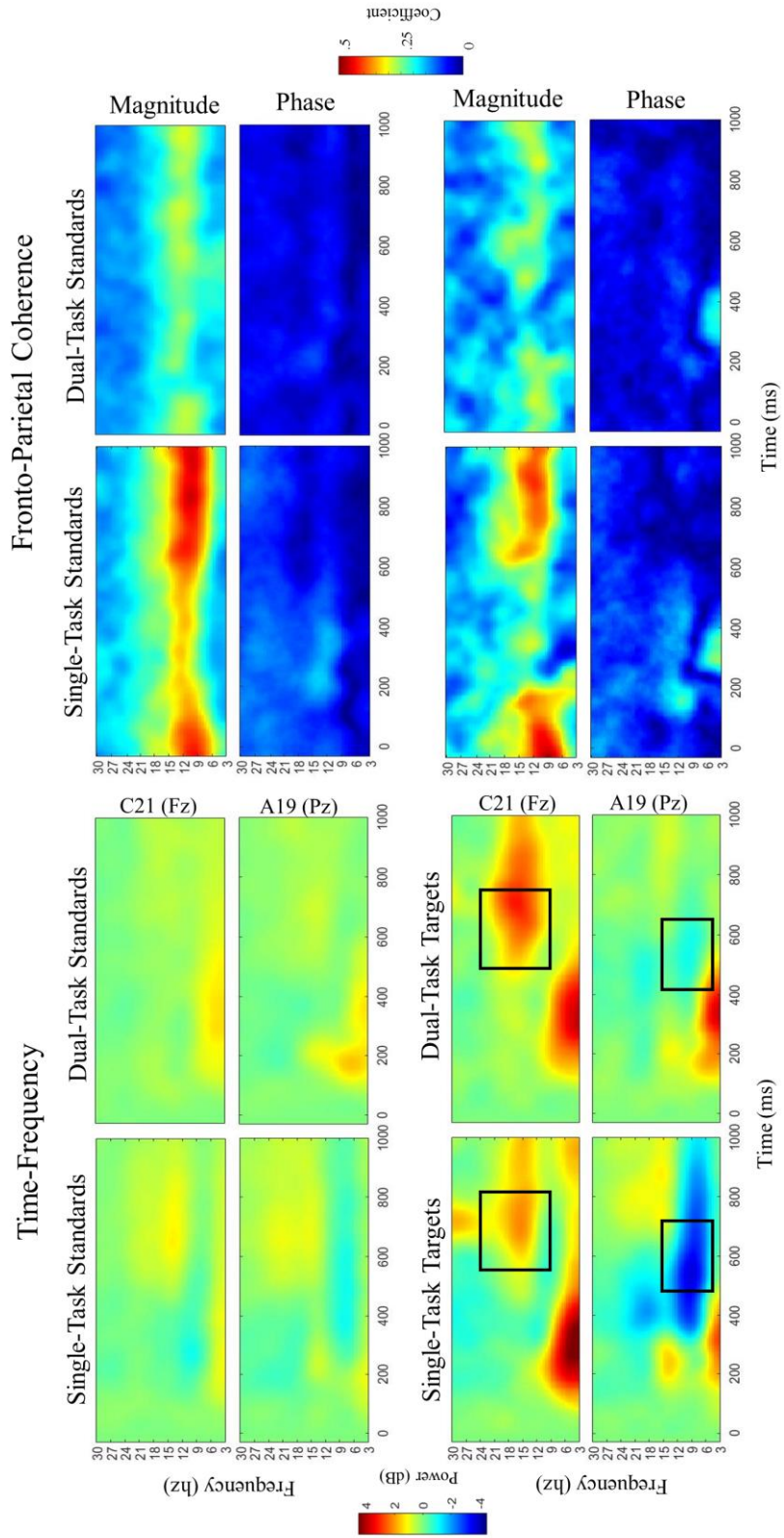
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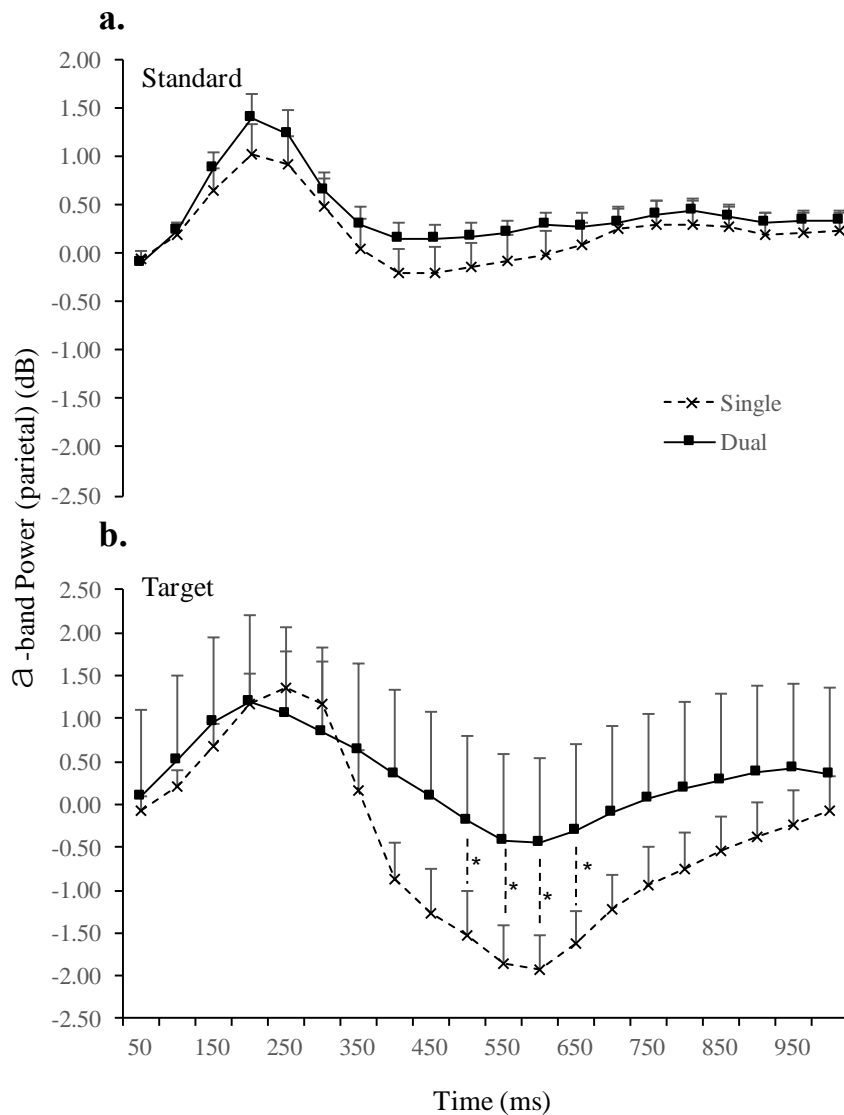
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FIGURE 4



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FIGURE 5

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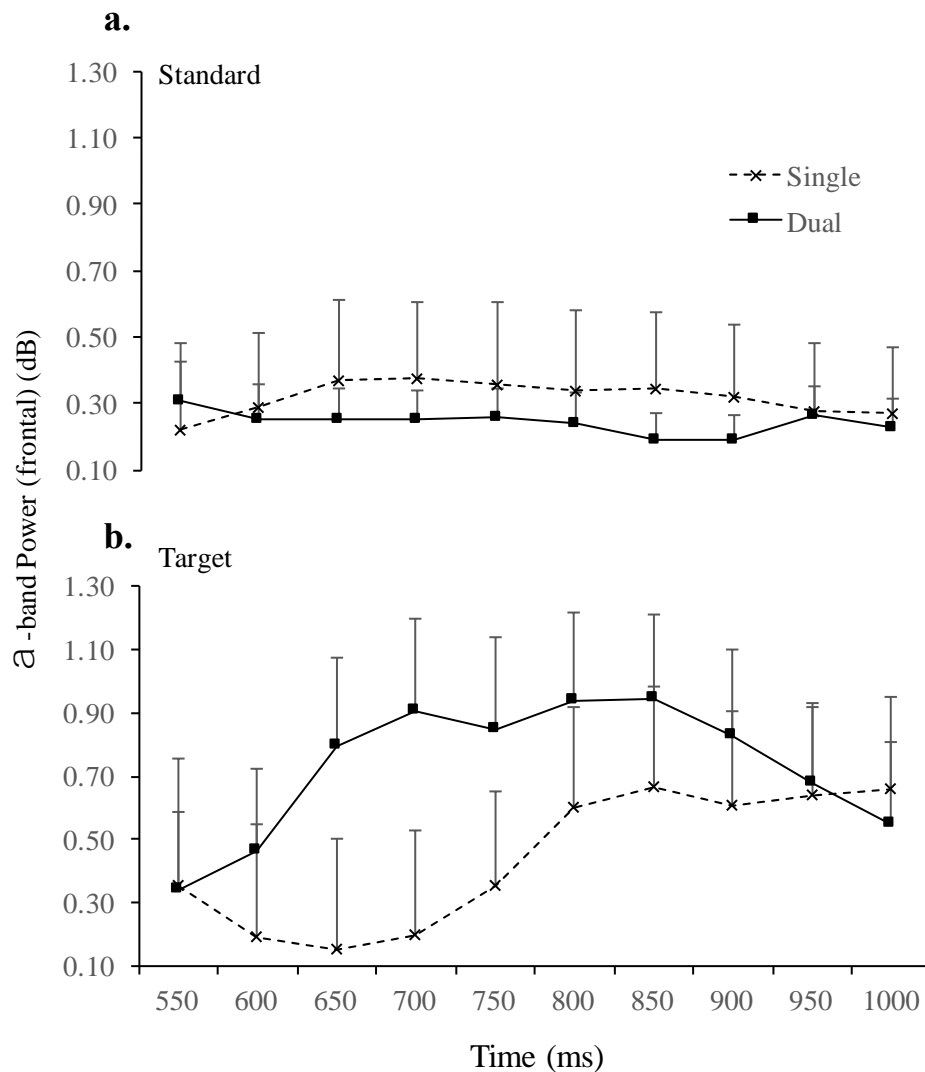
518 *Frontal alpha-band power*519 On frontal alpha-band power, there were significant stimulus x time ($F(9, 207) = 2.28, p < .05,$ 520 $\eta_G^2 = .006$), and task x stimulus x time ($F(9, 207) = 3.17, p < .001, \eta_G^2 = .005$) interactions.

521 Frontal alpha-band power was greater in the dual than single task for target stimuli,

522 particularly in the 650-750 ms period (Figs. 4, 6). There was no corresponding difference for

523 the standard stimuli.

524

525 **FIGURE 6**

526

527 *Fronto-parietal alpha-band coherence*528 On amplitude coherence, there were significant main effects of task ($F(1, 23) = 31.99$,529 $p < .001$, $\eta_G^2 = .014$) and time ($F(19, 437) = 6.25$, $p < .001$, $\eta_G^2 = .011$), and significant530 interactions between task and time ($F(19, 437) = 2.72$, $p < .001$, $\eta_G^2 = .037$) and stimulus type531 and time ($F(19, 437) = 2.17$, $p < .001$, $\eta_G^2 = .003$). The time profile of amplitude coherence

532 was similar in single and dual task, with a period of attenuation centered around 500 ms post

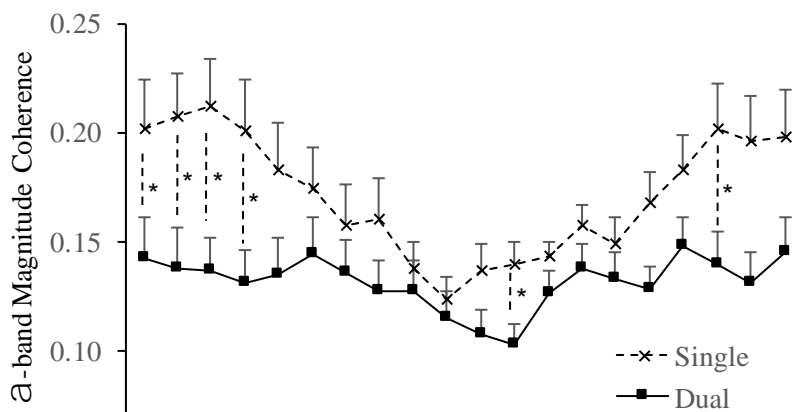
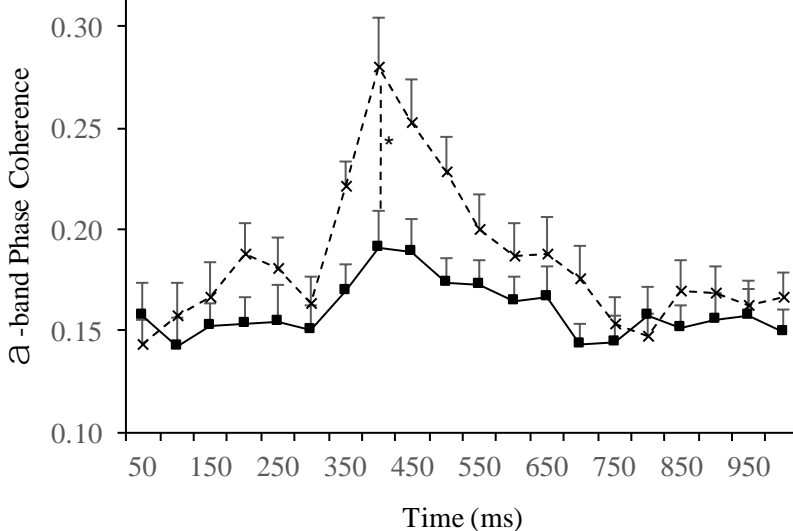
533 stimulus-onset, but overall, coherence amplitude was lower during dual tasking (Figs. 4, 7a).

534 In the case of phase coherence, there were main effects of task ($F(1, 23) = 13.29$, $p < .001$,

535 $\eta_G^2 = .004$), stimulus ($F(1, 23) = 59.11, p < .001, \eta_G^2 = .016$) and time ($F(19, 437) = 10.01,$
 536 $p < .001, \eta_G^2 = .017$), and significant task x time ($F(19, 437) = 1.79, p < .001, \eta_G^2 = .015$) and
 537 task x stimulus x time ($F(19, 437) = 2.5, p < .001, \eta_G^2 = .001$) interactions. The three-way
 538 interaction was due to the spike in phase coherence that occurred for target stimuli in the
 539 single task, but was not matched during dual-tasking (Figs. 4, 7b).

540

541

FIGURE 7**a.****b.**

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544

545 *Visuomanual Tracking Deviation*

546 Tracking performance during the single and dual task conditions is shown on the timeline in
 547 Fig. 2d). It can be seen that, in the dual-task trials that presented the target stimulus, the
 548 controlled dot developed a lead over the lead dot in both the horizontal and vertical directions
 549 during the 600-800 and 800-1000 ms periods post stimulus-onset. Fig. 8 shows the spatial
 550 pattern of the lead and controlled dot's trajectories in the single-task motor, and dual-task
 551 target- and standard-stimulus conditions. The main figure shows that the controlled dot's
 552 trajectory deviates prominently in the dual-task, target-stimulus condition only. A magnified
 553 inset shows this deviation pattern in six representative participants.

554

555 **FIGURE 8**

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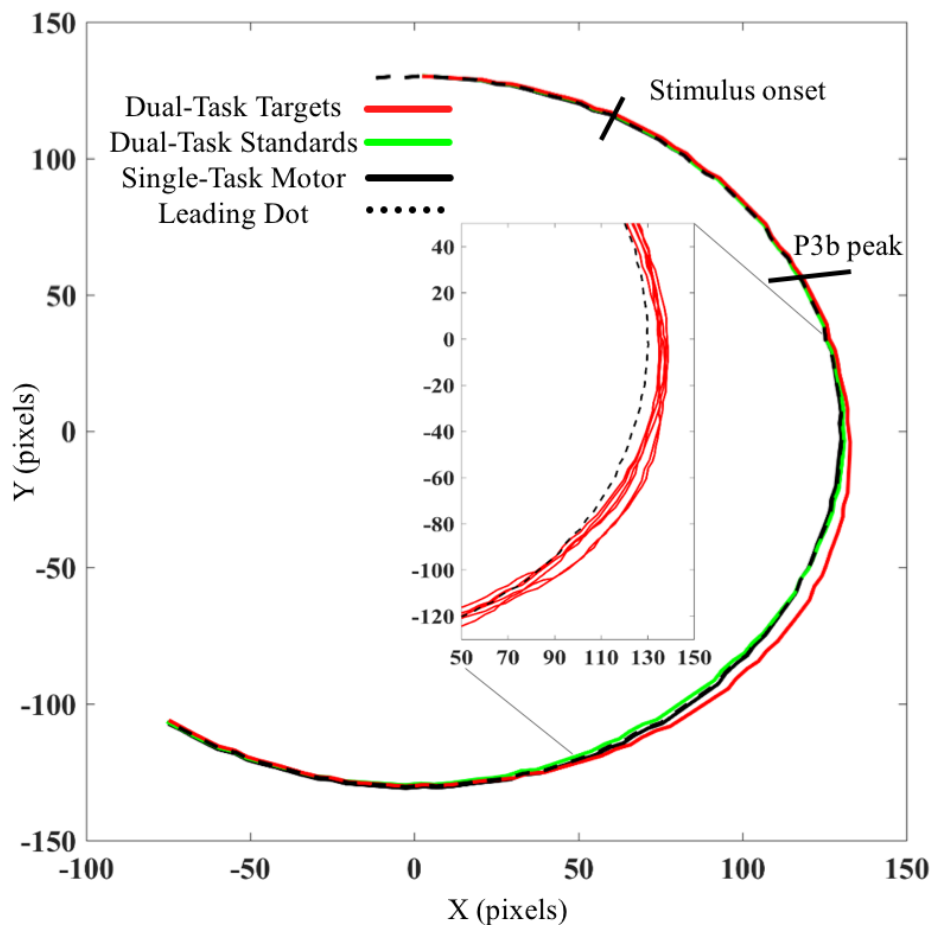
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570 Both the horizontal and vertical components of this deviation pattern were quantified using a
571 3 (task: motor-only single task, dual task with standard stimulus, dual task with target
572 stimulus) x 6 (time: 0-200, 200-400, 400-600, 600-800, 800-1000, 1000-1200 ms) repeated
573 measures ANOVA. In the case of horizontal deviation, the main effect of task was significant
574 ($F(2, 46) = 7.72, p < .001, \eta_G^2 = .097$), as was the main effect of time ($F(6, 138) = 4.44,$
575 $p < .001, \eta_G^2 = .062$). The interaction between task and time was also significant ($F(12, 276) =$
576 $6.12, p < .001, \eta_G^2 = .058$). Comparison of means indicated that horizontal deviation in the
577 dual-task target condition differed significantly from the other conditions in the 600-800 and
578 800-1000 ms time periods (see Fig. 2d). In the case of vertical deviation, the main effect of
579 time ($F(6, 138) = 3.18, p < .01, \eta_G^2 = .041$) and the interaction between task and time ($F(12,$
580 $276) = 2.72, p < .01, \eta_G^2 = .043$) were significant. In post-hoc means comparisons, however,
581 there were no significant differences between conditions in any of the time windows.

582

583 *Relationship between P3b amplitude and visuomanual tracking deviation*

584 The dual-task target-stimulus condition produced a significant tracking deviation in the 500
585 ms time period following the P3b peak. As the P3b component corresponds to the recognition
586 of the stimulus' task relevance, the observed trajectory deviation in fact occurred during the
587 subsequent executive function of updating the target tally. To test whether tracking deviation
588 may have been related to the P3b process, we correlated the P3b peak amplitudes with the
589 maximum horizontal and vertical tracking deviations that followed. Neither horizontal ($r =$
590 $.126, p = .56$) nor vertical ($r = -.06, p = .77$) deviation was significantly correlated with the P3b
591 peak amplitude.

592

593

594

595 *Effects of oddball task performance on spectral power over primary motor cortex*

596 Visuomanual tracking occurred in three task conditions: motor-only, dual-task with the
597 standard stimulus, and dual-task with the target stimulus. In these three conditions, we
598 expected to observe event-related desynchronization (ERD) over motor cortex relative to the
599 single-task standard and target oddball conditions (where there was no motor activity).
600 Additionally, recall that if performing the oddball task while tracking reduced motor
601 resourcing, we expected less ERD (more spectral power) in the two dual-task conditions
602 relative to the motor-only condition. Separately for alpha and beta power bands, we
603 conducted a 2 (hemisphere: LH, RH) x 5 (task: single-standard, single-target, dual-standard,
604 dual-target, motor-only) repeated measures ANOVA using absolute power as the dependent
605 measure (Fig. 9).

606

607 For the alpha band (Fig. 9a), the main effects of hemisphere ($F(1, 23) = 14.09, p < .001, \eta_G^2 =$
608 $.012$), and task ($F(4, 92) = 13.88, p < .001, \eta_G^2 = .092$) were significant, but the interaction
609 between hemisphere and task was not. For the beta band also (Fig. 9b), the main effects of
610 hemisphere ($F(1, 23) = 13.98, p < .001, \eta_G^2 = .012$), and task ($F(4, 92) = 19.29, p < .001, \eta_G^2 =$
611 $.084$) were significant, but the interaction between hemisphere and task was not. As Fig. 9
612 indicates, spectral power over motor cortex was reduced (i.e., ERD occurred) in the three task
613 conditions involving tracking. Post-hoc mean comparisons did not find differences between
614 the dual-task and motor-only conditions in either band, which suggests that motor
615 programming resourcing was not impacted as a result of concurrently performing the oddball
616 task.

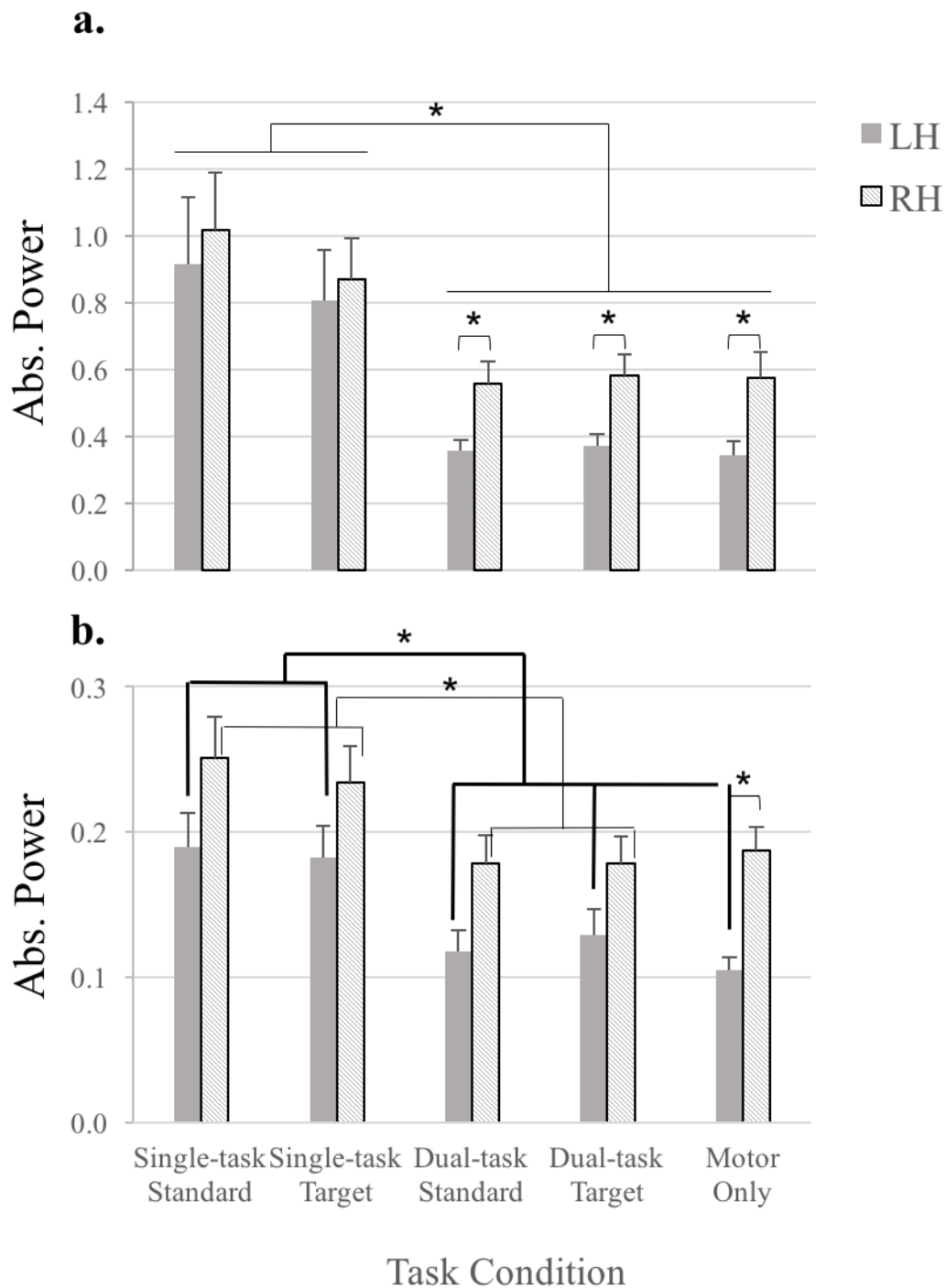
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FIGURE 9



621

622

In case any power differences occurred over shorter durations and therefore could not be

623

detected over the whole trial period, we also analysed spectral power over left primary motor

624

cortex (contralateral to the moving hand) using a 3(task: motor-only, dual-

625

target) x 6 (time: 0-200, 200-400, 400-600, 600-800, 800-1000, and 1000-200 ms) repeated

626 measures ANOVA. There were no significant effects, indicating that spectral power over
627 motor cortex did not change across the motor-only and dual-task standard and target
628 conditions.

629

630 **Discussion**

631 Performing the visual oddball task during visuomanual tracking reproduced performance
632 deficits that are characteristic of dual-task interference. The participants made more errors in
633 reporting the number of targets in the dual-task condition, and they also generated greater
634 positional deviation in the tracking task, but only following the onset of target stimuli in the
635 oddball task. Investigating these dual-task costs at the level of electrophysiological events
636 generated significant new information, both about the possible selectivity of dual-task costs
637 with respect to cognitive sub-processes, as well as asymmetry and asynchrony in reciprocal
638 effects.

639

640 First, at around 100 ms, there was no dual-task effect on P1 component amplitude. Thus,
641 there was no indication that tracking affected bottom-up perceptual processing of stimuli at
642 this timescale. The stimulus effect (a larger P1 magnitude for the target stimulus which had
643 greater contrast) under both single and dual task conditions also indicated that visual
644 engagement in the tracking task did not compromise early-stage perceptual processing of the
645 oddball stimulus. The P1 results suggest that the single and dual-task conditions were
646 comparable in terms of participants' ability to visually detect the oddball stimulus. Note that
647 participants' instructions throughout were to maintain eye-fixation at the center of the screen
648 region where task stimuli appeared. So, eye movements, such as pursuit of the leading dot
649 during tracking, played a minimal role, if any.

650

651 At 200 and 300 ms post stimulus-onset, dual-tasking did affect top-down
652 categorization/template-matching (P2) and task-relevance judgement (P3b) processes. The P2
653 component is thought to signify top-down processes involved in comparing the current
654 stimulus to representations of previous ones, such as the templates of standard and target
655 stimuli in this oddball task (Kim et al. 2008; Luck 2005). The P3b is linked to the
656 identification of the stimulus as a target, and hence its relevance to the response process
657 (Polich 2007; Luck 2005). Attenuation of both component amplitudes during dual-tasking
658 indicates that the resourcing of these top-down processes was compromised during
659 concurrent performance of the tracking task.

660

661 The results of time-frequency analysis of EEG corroborated the ERP evidence of reduced
662 resourcing of the oddball task during dual-tasking. The comparatively rarer encounter with
663 the target stimulus is a change in processing that should instigate a parietal alpha-band ERD
664 around 400-600 ms post stimulus-onset (Sutouh et al. 2000). During dual-tasking, we observed
665 a significant reduction in this parietal ERD's magnitude in the 450-650 ms time bin (Fig. 4,
666 bottom-left panel), indicating that the neural process of target identification was not as robust
667 as in the single-task situation. This result was also reflected behaviorally in reduced target-
668 detection accuracy in the dual-task condition.

669

670 In addition to the above, concurrent performance of the tracking task was also found to affect
671 the strength of the fronto-parietal network (Corbetta and Shulman 2002) that supports
672 attention tasks such as oddball detection (Sauseng et al. 2006; Güntekin and Başar 2010;
673 Sadaghiani et al. 2012; van Schouwenburg et al. 2017). The dual-tasking condition showed
674 lower alpha-band magnitude and phase coherence between frontal and parietal networks,
675 indicating that the large-scale cortical coordination that links bottom-up and top-down

676 processes in attentional tasks was eroded when simultaneously performing the tracking task.
677 We also observed increased frontal alpha-band power in the dual-task condition, which
678 confirms that overall WM load increased while dual-tasking relative to the single task, as has
679 also been observed in imaging studies of cognitive-motor dual-task interference (Holtzer et
680 al. 2011; Doi et al. 2013; Meester et al. 2014; Leone et al. 2017).

681

682 These results show that concurrent visuomanual tracking had a negative impact on oddball
683 task processes in the P2 and P3b time periods, suggesting that this type of CSC-cognitive
684 dual-tasking reduces attentional resources available to the cognitive task. Reciprocally,
685 however, no positional errors in tracking accumulated during these time periods. Performing
686 the tracking task reduced the accuracy of oddball target detection, which could have resulted
687 from interference in the P2-P3b timescale (where the waveforms were magnitude-attenuated
688 when dual-tasking) or later during the executive function of updating the tally, or both (Fig.
689 1). In the reverse direction, the impact of oddball detection on tracking performance occurred
690 only in the period after the P3b waveform, and then only in trials where the target stimulus
691 was encountered. Moreover, the magnitude of tracking deviation was not correlated with that
692 of the magnitude of the preceding P3b component. The fact that tracking deviation occurred
693 only in the case of the target stimulus (which has also been observed previously see Gazes et
694 al. 2010, for example), and that its magnitude was unrelated to that of the preceding P3b,
695 together preclude the possibility that an earlier, more general interference resulted in delayed
696 effects in the post-P3b response stages. Rather, the observed pattern strongly suggests that it
697 was the cognitive response triggered by the target stimulus (i.e., the executive function of
698 updating the target tally) that interfered with tracking. In this sense, the updating process
699 could be considered a (cognitive) perturbation to the tracking coordination. Note that the
700 tracking errors observed following target stimuli amounted to a phase advance relative to the

701 lead stimulus (Fig. 2d), whereby the controlled cursor extended beyond the circle traced by
702 the lead dot (Fig. 8). This pattern suggests that the perturbation, owing to the updating
703 process in the target condition, did not affect the participants' ability to generate hand motion
704 per se, but rather impeded their ability to entrain the motion to the lead stimulus by keeping
705 centripetal acceleration constant. In this respect, the pattern seen here differs from the pauses
706 to tracking that were seen when postural perturbations were applied while visuomanual
707 tracking was performed as a secondary task (McIlroy et al. 1999; Norrie et al. 2002).
708 Previous research has also shown that reaction time to visual or auditory stimuli can be
709 slowed when a perturbation is applied to a concurrent balancing function (e.g., Redfern et al.
710 2002). It is possible then, that the cognitive perturbation, owing to updating in the oddball
711 task, slowed participants' response to visual feedback of accumulating error while tracking
712 on a circular path.

713

714 The interference pattern observed here shows that simply documenting reciprocal
715 performance deficits at the behavioral level is not sufficient for understanding the micro-
716 structure of interference between a CSC and a concurrent cognitive task. It is possible that, as
717 in the present task combination, the CSC impacts the attentional components of the cognitive
718 task, but it is an executive function component of the cognitive task that impacts the CSC.
719 Also, these directional influences can occur at different times in the information-processing
720 sequence. Such a finding was made possible in this study by the use of a multi-component
721 cognitive task, and the deployment of neurophysiological methods to resolve interference
722 effects to the specific time-scales of task components. The possibility or significance of such
723 asymmetric and asynchronous CSC-cognitive interference has never been highlighted in the
724 large and growing dual-tasking literature on everyday CSCs (e.g., driving, gait, or balancing).
725 This is despite the fact that the vast majority of everyday cognitive tasks performed alongside

726 common CSCs involve perception, attention, and executive functions, as well as a motor
727 response in some cases.

728

729 Even using highly controlled laboratory tasks, it is rarely possible to arrange that the
730 cognitive task only taps a single cognitive sub-process such as attention or EF. Everyday
731 cognitive activities almost always combine a number of sub-processes. In addition, multiple
732 simultaneous task demands activate executive attention processes that dynamically adjust
733 cognitive resource allocation (Ridderinkhof, van den Wildenberg, Segalowitz, and Carter
734 2004). In the present study, performing the CSC alongside the oddball task evidently put
735 pressure on available attentional resources, as indicated by attenuated P2, P3b, and parietal
736 alpha-band ERD. However, this did not have a reciprocal effect on CSC performance in the
737 same timescale. Thus, reduced resourcing of the cognitive task rather than the CSC was the
738 preferred solution for dual-task demands at that timescale. This pattern is also seen in the
739 context of whole-body CSCs such as gait or balancing, where priority is normally given to
740 CSC maintenance at the expense of cognitive performance (e.g., the ‘posture-first’ principle)
741 (Bloem et al 2001). Although, this strategy is stable for healthy young adults, in older people,
742 particularly neurological patients, prioritization in the face of dual-task pressure does not
743 always favour the CSC (Yogev-Seligmann et al. 2008). Parkinson’s (Bloem et al 2001) and
744 stroke patients (Huitema et al. 2006) may prioritize the secondary task over gait or balancing,
745 and even healthy older adults can prioritize their planning of future stepping at the risk of
746 losing balance (Chapman and Hollands 2007). In this study, close inspection of the
747 electrophysiological events associated with multiple cognitive sub-processes enabled the
748 observation that CSC performance was maintained at the expense of resourcing the
749 attentional component of the cognitive task in the 200-400 ms timescale, but this was not to
750 achieve later at the timescale of the EF component of the oddball task.

751 As previously outlined, there is converging evidence that CSC stability is most consistently
752 impacted by concurrent EF tasks. Even though CSC performance in the present study
753 remained unperturbed as the oddball task's attentional sub-processes came under resourcing
754 pressure, CSC errors did occur later during the EF sub-process of the same task. As the
755 present task setting did not allow strategic adaptations (e.g., reducing CSC speed), or
756 utilization of the kind of error tolerance that is inherent in everyday CSCs such as driving or
757 walking, it provided strong evidence that concurrent demands for EF operations may be at the
758 heart of CSC-cognitive interference. There is not a universally accepted list of the types of
759 cognitive operations that comprise EF. In the context of CSC-cognitive dual-tasking, Yogeve-
760 Seligmann et al. (2008) identified volition (formulating goals, initiating action), self-
761 awareness, planning (identifying and organizing sub-tasks), response-inhibition (disregarding
762 irrelevant information), response-monitoring (detecting errors with respect to task goals) and
763 attention allocation (distributing available cognitive resources among competing demands) as
764 aspects of EF. An alternative to this functional approach has been to associate EF with
765 specific operations performed on information held in WM. Miyake and colleagues (Miyake et
766 al. 2000; Miyake and Friedman 2012) have proposed, for example, that EF involves updating
767 (monitoring and altering WM contents), shifting (moving resources between task sets) and
768 inhibition (suppressing effects of irrelevant information).

769

770 In terms of the latter approach, the EF component of the covert oddball task used in the
771 present study was updating (the tally of target stimuli detected). CSC-cognitive dual-tasking
772 have frequently addressed shifting (e.g., slowing down the CSC to accommodate cognitive
773 operations) and inhibition (e.g., using Stroop tasks), but the effects of updating operations on
774 a concurrent CSC's stability have not been highlighted. It might be that detecting the impact
775 of updating was only made possible by severely curtailing the opportunity for shifting (by

776 preventing speed variation). Updating task-relevant information in WM is patently ubiquitous
777 in everyday cognitive activity. Indeed, shifting between task sets must also involve large-
778 scale updating of which information is currently task-relevant, and even inhibition is only
779 possible when the current task-relevance of information is kept updated. Even as updating
780 processes are recognized as fundamental to performing or switching between cognitive tasks,
781 it is worth noting that frequently updating the state is also fundamental to the maintenance of
782 any CSC. This form of state-updating must integrate sensorimotor information on a grand
783 scale, be tailored to the current task goals held in WM, and, importantly, maintain a high
784 enough frequency to ensure CSC stability or counteract perturbations to it. It is highly
785 plausible that pre-frontal cortex activity detected during CSCs, such as walking (Harada et al.
786 2009; Suzuki et al. 2004), is associated with state-updating. The extent to which updating
787 operations can be performed simultaneously with respect to more than one task could be a
788 key point in understanding CSC-cognitive interference, and indeed, dual-task interference
789 more generally. It has been shown that just like CSC-cognitive dual-task performance,
790 updating performance in EF tasks also declines with age (De Beni and Palladino 2004). Our
791 results suggest that future research should focus on the possibility that the EF of updating is
792 at the heart of CSC-cognitive interference.

793

794

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FIGURE CAPTIONS

FIGURE 1. (a) Dual-task arrangement. The oddball stimulus is either an unfilled (standard) or filled (target) circle in the centre of the screen. The tracking lead is the blue dot circling the oddball stimulus clockwise. The participant tracks the blue dot using a stylus on the digitizing tablet. Stylus position is displayed as a black dot on the screen. (b) Schematic representation of concurrent task demands (see text for details).

FIGURE 2. a-c: ERP difference waves derived from (a) right occipital, (b) fronto-central, (c) parietal electrode clusters, showing, respectively, P1, P2 and P3b waveform differences (target–standard, average referenced) in single and dual task conditions. Areas shaded in blue show statistically significant differences. No significant differences between single and dual-tasks were found for P1 (a). Both P2 and P3b show statistically significant differences between single and dual-task difference waves (b, c). The corresponding scalp topographies are of difference waves at 120, 200, and 400 ms post stimulus-onset. (d) Epoched tracking deviation (pixel difference between the controlled and leading dots) in the horizontal (top) and vertical (bottom) axes. The dotted vertical line at ~400ms indicates mean P3b peak latency. Both vertical and horizontal tracking deviation increased for dual-task target trials in the 600-800 ms and 800-1000 ms periods. Tracking results are shown separately for the oddball task’s standard and target trials, and for the single-task condition in which participants only performed the tracking task.

FIGURE 3. (a) Mean P1, P2 and P3b ERP component amplitude differences (target-standard) for both single and dual task conditions. Both P2 and P3b difference wave amplitudes were

964 significantly attenuated in the dual-task condition. Error bars show standard errors.

965

966 FIGURE 4. Grand average time-frequency representation and fronto-parietal coherence of
967 standard and target trials in single and dual task conditions. Left panels: spectral power
968 changes (dB) as a function of time for standard (top) and target (bottom) trials at C21
969 (frontal) and A19 (parietal) electrodes; Right panels: event-related spectral coherence
970 (ERSCoh) between C21 and A19 for standard (top) and target (bottom) trials. Parietal alpha
971 desynchronization is shown for single-task target trials relative to dual-task target trials in
972 the bottom two cells of the left panel. Frontal alpha synchronization for dual-task target
973 trials relative to single-task can also be seen in the bottom left panel. Fronto-parietal alpha
974 magnitude and phase coherence (right panel) can be seen to decrease during dual-task
975 standard and dual-task target trials relative to single-task trials.

976

977 FIGURE 5. Mean parietal alpha power (dB) for standard and target trials in single and dual
978 task conditions. (* Bonferroni-corrected significant difference). Parietal alpha power
979 decreases for single-task target trials (alpha desynchronization) in the 500-700ms period
980 relative to dual-task targets. Error bars show standard errors.

981

982 FIGURE 6: Mean frontal alpha power (dB) for both standard and target trials in single and
983 dual task conditions at 10 time points from 550 to 1000 ms. Frontal alpha power increases
984 for dual-task target trials (alpha synchronization) in the 650-750 ms period relative to
985 single-task targets. Error bars show standard error.

986

987 FIGURE 7: Mean fronto-parietal magnitude (a) and phase (b) coherence for target stimuli in
988 both single and dual task conditions at 20 time points from 50 to 1000 ms (* Bonferroni-

989 corrected significant difference). Fronto-parietal alpha magnitude and phase coherence are
990 shown to be attenuated during dual-task target trials relative to single-task target trials.
991 Error bars show standard errors.

992

993 FIGURE 8. Grand average epoched horizontal (X) and vertical (Y) deviation (pixels) in the
994 manual tracking task. Stimulus onset time and mean P3b peak latency are marked by black
995 lines crossing the time series. The insert shows a magnified view of X and Y deviation for
996 dual-task target trials for six representative participants. In the target trials, the controlled
997 dot's trajectory extended beyond the circular trace of the lead dot, indicating that
998 participants were impeded in their ability to keep their motion entrained to that of the lead
999 dot by maintaining a constant centripetal acceleration.

1000

1001 FIGURE 9. Alpha (a) and beta (b) band power over left and right primary motor cortex
1002 during all single and dual task conditions. Power was attenuated in the dual-task and motor-
1003 task only conditions, indicating desynchronization linked to motor activity.
1004 Desynchronization was greater in LH (the motor task used the right hand), but did not differ
1005 in either frequency band between the dual-task and motor task-only conditions. Error bars
1006 show standard errors.

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