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Age-related changes in the interference between cognitive task components and concurrent sensorimotor coordination

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ABSTRACT

Continuous sensorimotor coordinations (CSCs) such as driving, walking, using control interfaces or maintaining the body's balance are often performed alongside concurrent cognitive tasks involving attention and executive function. A range of these task combinations show interference, particularly in older adults, but the timing, direction and reciprocity of interference is not yet understood at the level of the tasks' information-processing operations. This paper compares the chronometry of dual task interference between a visual oddball task and a continuous visuomanual tracking task performed by young and older adults. The oddball task's constituent operations were identified using electrophysiological correlates, and deviations in the tracking task reflected perturbations to state monitoring and adjustment characteristics of CSC tasks. Despite instructions to give equal priority to both tasks, older participants maintained a high level of resourcing of the oddball task when dual tasking whereas young participants reduced resourcing to accommodate the demands of the tracking task. Older participants had a longer period of tracking inaccuracy during the executive function component of the oddball task, and unlike in young participants, this decrement was also observed when the stimulus was not a target and the executive function of updating the target tally was not required. These detailed chronometric results clarify that age-related amplification of CSC-cognitive interference are largely due to greater inflexibility in task prioritization. Prioritization of the cognitive task over the CSC in this type of dual tasking may have safety implications in everyday task settings.

1. Introduction

A common type of everyday dual task involves an attention-demanding cognitive task performed while maintaining a continuous sensorimotor coordination (CSC). For example, a visual target such as a sign with known features may need to be identified among non-targets, and a decision or action taken, while maintaining a CSC like driving a motor vehicle, walking along a path, or tracing or tracking a trajectory with an instrument (e.g., a pen or a controller such as a joystick or a computer mouse). In the case of driving, dual task effects have been of significant interest due to the potential of interference from telephone conversations (Mac-Auliffe et al., 2021; Recarte and Nunes 2003; Strayer and Johnston 2001), whereas in the case of walking or maintaining the body's balance, concurrent cognitive load is a recognized risk factor in falling in old age (Amboni et al., 2013; Rubenstein, 2006). Declining dual task performance is a notable feature of normal aging (Fraizer and Mitra, 2008; Springer et al., 2006) as well as neurological

conditions such as dementia (IJmker and Lamoth, 2012) or Parkinson's disease (Bloem et al., 2001; Yogev-Seligmann et al., 2008). A range of cognitive tasks interact with everyday CSCs such as driving (Beede and Kass, 2006; Nijboer et al., 2016), walking (Al-Yahya et al., 2011) and balancing (Fraizer and Mitra, 2008), and a higher level of interference between these tasks is observed in older age (Albinet et al., 2006; Li and Lindenberger, 2002; Papegaaij et al. 2017; Voelcker-Rehage et al., 2006).

CSCs and concurrent cognitive tasks may mutually interfere because they access the same capacity-limited information-processing mechanisms such as attention and executive function (EF). EF is considered a key locus of interference in the case of driving (Nijboer et al., 2016; Recarte and Nunes, 2003) and gait (Al-Yahya et al., 2011; Amboni et al., 2013). EF involves manipulating task-relevant information and allocating resources as required (Baddeley, 2007). This includes updating (monitoring and altering working memory contents), shifting (switching between task sets), and inhibiting irrelevant information or processes

(Miyake and Friedman, 2012). Another source of interference, commonly considered in balance research (Woollacott and Shumway-Cook, 2002), is competition for limited attentional resources (Leone et al., 2017). Recent research on cognitive-CSC dual tasking has focused on gross motor functions such as walking and balancing. These motor tasks affect the body's safety by preventing falling and therefore have an exigency that may not apply to fine motor coordination of the upper limbs such as in aiming, tracking or marking time. As such, the commonly observed prioritisation of postural tasks (Lion et al., 2014) by older people during cognitive-CSC dual tasking may not apply to fine motor control tasks as well. Although some studies requiring cognitive tasks concurrently with fine motor coordination have reported a tendency in older people to prioritize motor performance (Albinet et al., 2006), others have observed greater deterioration in motor performance (Corp et al., 2018; Gazes et al., 2010; Guillery et al., 2013; Johannsen et al., 2013; Remy et al., 2010; Voelcker-Rehage et al., 2006).

Aside from the possible differences in prioritization between postural and fine motor tasks, at least three methodological challenges impede a precise understanding of the mechanisms of cognitive-CSC interference (Baker et al., 2018). First, most cognitive tasks involve perceptual, attentional and EF operations in a temporal sequence, making it difficult to identify the precise locus of interference using cumulative behavioral measures such as accuracy, response time, and motor trajectory. Recent studies are addressing this by directly investigating brain processes using fMRI, fNIRS or EEG (Leone et al., 2017). Second, CSC task speed is frequently reduced (Haigney et al., 2000), particularly by older people (Al-Yahya et al., 2011), to accommodate the operations of a cognitive task, potentially masking the mechanisms of resource conflict (Mac-Auliffe et al., 2021). Third, everyday CSCs have some precision tolerance built into them. For example, highway lanes or walking paths are wide enough to allow a level of trajectory deviation without compromising safety or overall task goals (Nijboer et al., 2016; Springer et al., 2006). This allows accepting a higher level of deviation to accommodate any cognitive task operations that make demands on common cognitive resources (Mac-Auliffe et al., 2021).

The present study investigated differences between healthy young (Y) and older (O) people in the interference between cognitive and fine motor CSCs using a paradigm that addresses these three challenges. Following Baker et al. (2018), this study uses a cognitive task, visual oddball detection, that required in each trial a sequence of detecting the stimulus, identifying it as a target, and if it is a target, tallying the number of targets in the current trial block (Fig. 1). The stimulus detection and identification operations of this task (and their resourcing) are identifiable with precise timing by the event-related potentials P1 (perceptual detection), P2 (template-matching), and P3b (categorization of the stimulus as response-relevant). Reduced amplitude of these components indicates reduced resourcing of the operation in question, and increased latency reflects slower processing speed[1] (Polich, 2007). P1 occurs ~ 100 ms post stimulus over occipital sites, and its amplitude is responsive to bottom-up stimulus characteristics such as contrast and brightness (Johannes et al., 1995). The P2 component appears anteriorly ~ 200 ms post stimulus and is thought to indicate top-down mechanisms comparing the stimulus to representations of previous stimuli (including templates for standard and target stimuli) (Kim et al., 2008; Luck, 2014). The P3b component occurs posteriorly ~ 300–400 ms post stimulus and is thought to indicate the categorization of target stimuli as response-relevant (Luck, 2014; Polich, 2007). It was initially noted that, in O, the P3 might shift to a more anterior scalp distribution (Fabiani and Friedman, 1995; Pfefferbaum et al., 1984). More recent studies are suggesting that, rather than a relocation of the P3b, the

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[1] We analyzed P1, P2 and P3 latencies, but do not discuss these in this paper. There were no significant interactions between age group and single vs dual task, so latency effects did not inform the analysis of age-related differences in dual-task resourcing.
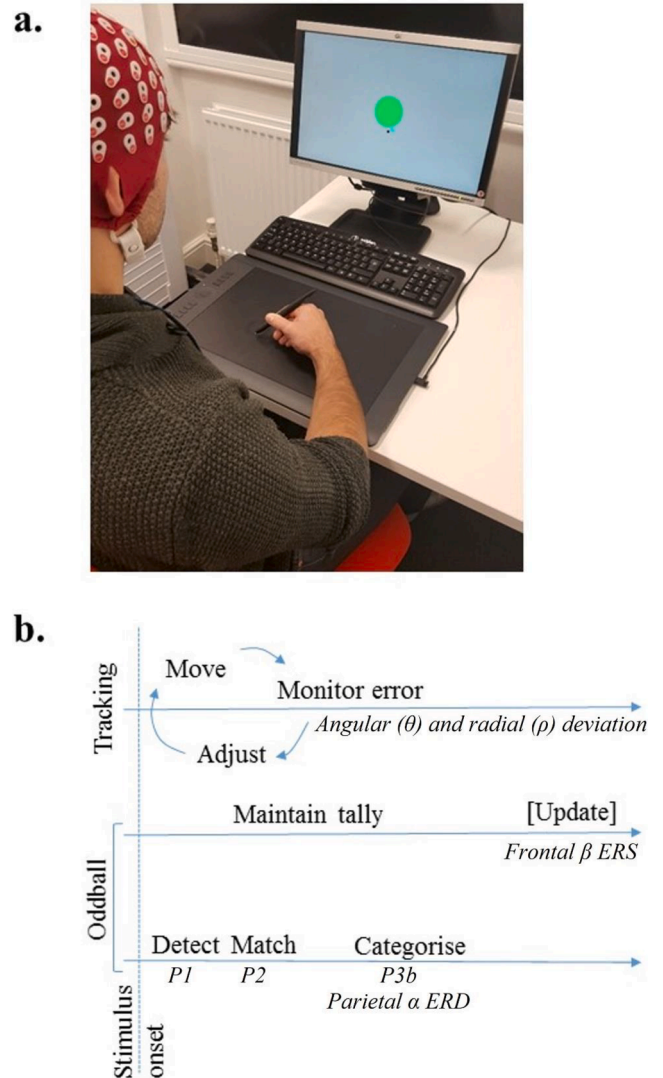
Fig. 1. (A) Task configuration. The oddball stimulus is either an unfilled (standard) or filled (target) circle in the centre of the screen. The tracking lead is the black dot circling the oddball stimulus clockwise. The participant tracks the black dot using a stylus on the digitizing tablet. Stylus position is displayed as a blue dot on the screen. (B) Schematic representation of concurrent task demands. The task components and the experimental measures that indicated their resourcing are shown according to their position on the timeline.

observed anterior shift may reflect the increased amplitude in O of a distinct and anterior P3a component that temporally overlaps the posterior P3b (Alperin et al., 2014a; Paitel and Nielson, 2021). This may indicate the recruitment of frontal executive functions as compensation for declining cognitive resources (Alperin et al., 2014b; Saliasi et al., 2013). In this study, we retained our focus on the posterior P3b of both age groups as an indicator of attentional resourcing. Our interest in the P3b was to note whether its amplitude was attenuated by dual tasking (which would indicate reduced attentional resourcing of the oddball task) in O as we have previously observed in Y (Baker et al., 2018), and whether O exhibited tracking deviations in the time-frame of the P3b (which we did not observe in Y). Aside from the P3b, we also used time–frequency analysis to measure event-related desynchronization (ERD) at parietal sites (Sutoh et al., 2000) in the 400–600 ms post-stimulus period. This ERD is expressed as a reduction in alpha band power over parietal sites, and is thought to indicate an attention-driven discrimination process (e.g., the detection of a change in processing when a rare target appears). Changes to this parietal alpha band ERD

due to age or dual tasking can therefore be indicative of changes in attentional resourcing (Spencer and Polich, 1999). We also tested the strength of coordination in the fronto-parietal network (Corbetta and Shulman, 2002) underpinning the oddball task as measured by the alpha band coherence between frontal and parietal activity (Güntekin and Basar, 2010; Sadaghiani et al., 2012; Sauseng et al., 2006; van Schouwenburg et al., 2017).

Following target identification processes, updating the target tally placed demands on working memory. We used time–frequency analysis to measure frontal beta-band power in the post-P3b period to indicate any changes in this working memory load due to age and dual tasking (Altamura et al., 2010; Pesonen et al., 2007). We also measured changes in neural resourcing of motor function by examining alpha band power over the contralateral motor cortex. Manual task execution results in event-related desynchronization (ERD) over the contralateral motor cortex (Pfurtscheller and Lopes da Silva, 1999). Reduced ERD (i.e., higher power) during dual tasking relative to the single task condition would indicate a reduction in resourcing the motor task. This study only investigated comfortable-speed CSC performance. The potential impact of CSC speed manipulation is raised in the discussion but left for future investigations.

The CSC task in this study was manually tracking a visual target on a circular path. This task enforced a set speed and continuously showed and measured even the smallest trajectory deviation. In quotidian tasks like walking or driving, error signals are salient only when a significant level of trajectory deviation accumulates (e.g., the walker comes too close to the edge of the path, or the driver approaches markings dividing highway lanes). In the present task (Fig. 1), in contrast, even the smallest tracking deviation (i.e., when the leading and controlled dots did not overlap on the screen) was visible and the instruction was to continuously minimise deviation. This ensured that participants could not reduce speed or lower tracking accuracy to accommodate dual task demands. In the dual task condition, the performance demands of the tracking task remained at the same level throughout the sequence of the oddball task's constituent operations. This tightly controlled task situation was expected to yield a temporally precise understanding of age-related changes in the symmetry and synchrony of interactions between the two tasks. The behavioral measures of tracking accuracy were the angular (θ) and radial (ρ) trajectory deviation.

Both the oddball and circular tracking tasks have been studied in older adults. In the oddball task, Y and O tend not to differ on accuracy (Amenedo and Díaz, 1998; Cid-Fernández et al., 2014; Cid-Fernández et al., 2016; Geerligs et al., 2014; Kaufman et al., 2016), with indications that O may detect more targets than Y, but also produce more false alarms (O'Connell et al., 2012). The inhibitory deficit hypothesis (Hasher and Zacks, 1988; Gazzaley and D'Esposito, 2007), which suggests that filtering of information deteriorates with age, may explain why O detect more targets, but also make more erroneous identifications. The declining ability to withdraw attentional resources from irrelevant stimuli may also correspond to physiological changes. For instance, when comparing target and non-target conditions, the scalp distributions of P2, P3 and fronto-central CRN (correct response negativity) amplitudes differ significantly in Y, but not in O (Amenedo and Díaz, 1998; Cid-Fernández et al., 2016; Friedman et al., 1998). P3 responses in O tend to have a similar pattern to Y, but with a smaller amplitude (Cid-Fernández et al., 2016; Czigler et al., 2006; O'Connell et al., 2012) and longer latency (Fjell and Walhovd, 2001).

In the case of fine motor CSCs, research shows age-related decline in performance in a range of tasks (Skoura et al., 2005), including bimanual tracking (Serbruyns, et al., 2015; van Ruitenbeek et al., 2017), finger tapping (Bangert, et al., 2010; Fling et al., 2012; Sallard et al., 2014), pointer tracing (Bock, 2005; Shetty et al., 2014), and the Purdue Pegboard task (Serbruyns, et al., 2015). In tracking tasks, however, O tend to show similar performance to Y (Bangert et al., 2010; Hocherman et al., 2004; Summers et al., 2010), with an age-related deficit emerging only at higher speeds (Riviere and Thakor, 1996).

As already noted, dual tasking with whole-body CSCs such as walking (Al-Yahya et al., 2011) or balancing (Fraizer and Mitra, 2008) find that O tend to prioritize the motor task (the posture-first principle) (Bloem et al., 2001; Liston et al., 2014). This is not always the case, however, as both O and neurological patients can be found in some cases to prioritize the cognitive over the motor task (e.g., Beurskens et al., 2014; Chapman and Hollands, 2007; Dubost et al., 2006; Liston et al., 2014; Yogev-Seligmann et al., 2008). Overall, O are more prone to showing dual task deficits (Lindenberger et al., 2000; Papegaaij et al., 2017), although task difficulty can play a major role in this (Boisgontier et al., 2013). In the specific case of dual tasking with manual tracking as the motor task, which we studied here, O usually exhibit more slowing (Vaportzis et al., 2014) and deviations (Hahn et al., 2011; Van Impe et al., 2011; Vaportzis et al., 2014) than Y, with greater costs on motor than cognitive performance (Van Impe et al., 2011). In this study, the motor task enforced a comfortable but fixed speed and its circular trajectory required continuous error checking and correction. We expected these restrictions to expose the age-related differences in the management of the underlying resource allocation problem when strategic changes to speed or precision are not possible.

In Baker et al's (2018) study, which tested the present task combination on Y only, dual tasking reduced the oddball task's accuracy and attentional resourcing (P2 and P3b amplitude were lower relative to the single-task condition, as was parietal alpha-band desynchronization). Tracking task performance was not affected in the time frame of the oddball task's attentional components. Instead, tracking deviation accumulated at a later time if the stimulus was a target and the requirement then was to update the mental tally of detected targets. This updating of the value of an item held in working memory is an EF (Miyake and Friedman, 2012), and it occurred only in trials where the stimulus was a target, suggesting that the oddball task component that interfered with concurrent tracking was the EF. These results were obtained under clear instructions to give equal importance to both tasks. Under identical conditions, the present study investigated whether there were any age-related changes to the asymmetric and asynchronous interference pattern observed by Baker et al. (2018) in Y. Previous research has produced mixed results with respect to which task's operations are prioritized by O when concurrent performance of cognitive and CSC tasks is required. In Baker et al. (2018), Y reduced their resourcing of the cognitive task's attentional components during dual tasking (as evidenced by attenuated P2 and P3b amplitude) and avoided accumulating tracking errors during these components' time frame. Here, we were interested in the extent to which this balancing of priorities would be shown by O, or a clear priority of one task would emerge to the detriment of the other. In the later time frame of EF (updating), where Y accrued tracking deviation in Baker et al. (2018), we expected O to fare worse, in terms of magnitude or the period of significant deviations, given the known age-related reduction in EF capacity. As in Baker et al. (2018), we factored out the effects of differences in preferred speed between Y and O by allowing each participant to track at their preferred speed.

In summary, this study used a visual oddball task and a circular tracking task to investigate age-related differences in dual task interference between a cognitive task with a sequence of perceptual, attentional and EF components and a continuous, fine motor control task performed at a comfortable but constant speed. The objective of this controlled test was to use neurophysiological measures to precisely locate signs of age-related differences in dual task interference in the perceptual, attentional and EF stages of the cognitive task's sequence of operations. The amplitudes of the ERP components P1, P2, and P3 indicated resourcing of the perceptual and attentional stages of the oddball task. Parietal alpha band power provided a measure of the neural resourcing of the attentional processes, and frontal beta band power in the post-P3b period indicated working memory load when the tally of targets was updated. Fronto-parietal magnitude coherence provided a measure of the strength of the oddball task's network. The

tracking task's performance was continuously measured as the instantaneous angular and radial deviations from the required trajectory. Any change in the cortical resourcing of the tracking task was measured using alpha band power over the contralateral motor cortex.

2. Results

2.1. Oddball task accuracy

Oddball task accuracy was analyzed using a 2 (Age: Y, O) $\times$ 2 (Task: ST, DT) mixed ANOVA with age as the between-subject and task as the within-subject factor. There were significant main effects of age [F(1, 43) = 37.44, $p <.001$, $\eta_p^2 = 0.47$; O had higher accuracy] and task [F(1, 43) = 16.82, $p <.001$, $\eta_p^2 = 0.28$; accuracy was lower in DT]. There was also a significant interaction between age and task [F(1, 43) = 13.46, $p <.01$, $\eta_p^2 = 0.24$; As shown in Fig. 2, O's accuracy exceeded Y's by 9.2% in ST and 29.4% in DT. O's accuracy did not change between ST and DT].

2.2. ERP measures of stimulus detection, template-matching and classification as task-relevant

Effects on the ERP component amplitudes (P1, P2, and P3b) were analyzed using 2 (Age: Y, O) $\times$ 2 (Task: ST, DT) $\times$ 2 (Stimulus: Standard, Target) mixed ANOVA with age as between-subject and task and stimulus as within-subject factors. The grand average ERP waveforms are summarized in Fig. 3.

2.2.1. Stimulus detection (P1)

P1 amplitude. There were significant main effects of age [F(1, 43) = 5.84, $p <.05$, $\eta_p^2 = 0.12$; P1 amplitude was greater in Y], task [F(1, 43) = 18.94, $p <.001$, $\eta_p^2 = 0.31$; P1 amplitude was greater in ST], and stimulus [F(1, 43) = 48.62, $p <.001$, $\eta_p^2 = 0.53$; P1 amplitude was greater for the target]. The interaction between age and stimulus was also significant [F(1, 43) = 4.82, $p <.05$, $\eta_p^2 = 0.10$]. The difference in P1 amplitude between target and standard stimuli was greater in Y than O (Fig. 4a). There were no other significant effects.

2.2.2. Template-matching (P2)

P2 amplitude. The main effect of stimulus was significant [F(1, 43) = 10.68, $p <.01$, $\eta_p^2 = 0.20$; P2 amplitude was greater for the target]. There was a significant interaction between age and task (F(1, 43) = 10.20, $p <.01$, $\eta_p^2 = 0.19$; Y had greater P2 amplitude than O in ST, but this difference disappeared in DT as Y's amplitude reduced but O's increased]. The interaction between age and stimulus was significant [F(1, 43) = 8.43, $p <.01$, $\eta_p^2 = 0.16$; P2 amplitude increased from standard to target stimuli in both Y and O, but this increase was greater in Y; Y and O did

not differ to corrected level for either stimulus]. The interaction between task and stimulus was also significant [F(1, 43) = 11.82, $p <.01$, $\eta_p^2 = 0.22$] but the three-way interaction was not. Fig. 4b illustrates the key pattern in the data. Y's P2 amplitude in ST and DT stayed the same for standard stimuli but reduced in DT for the target stimuli. In contrast, O's P2 amplitude increased in DT for standards. Y had significantly higher P2 amplitude than O for the target stimulus in the single-task condition.

2.2.3. Classification of stimulus as task-relevant (P3b)

P3b amplitude. There were significant main effects of age [F(1, 43) = 6.53, $p <.05$, $\eta_p^2 = 0.13$], task [F(1, 43) = 17.35, $p <.001$, $\eta_p^2 = 0.29$], and stimulus [F(1, 43) = 102.04, $p <.001$, $\eta_p^2 = 0.70$]. The interaction between age and stimulus was significant [F(1, 43) = 12.72, $p <.001$, $\eta_p^2 = 0.23$], as was the three-way interaction between age, task and stimulus [F(1, 43) = 6.6, $p <.05$, $\eta_p^2 = 0.13$]. As Fig. 4c illustrates, in the case of the target stimulus, Y's P3b amplitude reduced in DT compared to ST, but O's amplitude did not change.

2.3. Time-frequency analyses of EEG

2.3.1. Attentional resourcing (parietal alpha-band desynchronization)

Effects on parietal alpha-band power was analyzed separately for standard and target stimuli using 2 (Age: Y, O) $\times$ 2 (Task: ST, DT) $\times$ 20 (Time: 50–1000 ms at 50 s intervals) mixed ANOVA with age as the between-subject and task and time as within-subject factors. Fig. 5 summarizes the obtained results.

Target stimuli. There were significant main effects of age [F(1, 43) = 4.23, $p <.05$, $\eta_p^2 = 0.09$; overall power was lower for O], task [F(1, 43) = 13.77, $p <.001$, $\eta_p^2 = 0.24$; power was lower in ST], and time [F(19, 817) = 37.48, $p <.001$, $\eta_p^2 = 0.47$; as shown in Fig. 5, power reduction was in the 600–1000 ms time period in ST and the 600–800 ms period in DT]. The interactions between task and time [F(19, 817) = 9.25, $p <.001$, $\eta_p^2 = 0.18$] and time and age [F(1, 43) = 2.56, $p <.05$, $\eta_p^2 = 0.06$] were also significant. The significant ERD difference between Y and O was located in the 450–500 ms period in DT. There were no other significant effects.

Standard stimuli. There were significant main effects of task [F(1, 43) = 6.88, $p <.05$, $\eta_p^2 = 0.14$; power was lower in ST] and time [F(19, 817) = 16.11, $p <.001$, $\eta_p^2 = 0.27$], and a significant interaction between age and time [F(19, 817) = 4.66, $p <.001$, $\eta_p^2 = 0.10$; O had reduced power relative to Y in the 250–300 ms time period]. There were no other significant effects.

2.3.2. Post-P3b working memory load (frontal beta-band synchronization)

Effects on frontal beta-band power in the post-P3b period were analyzed separately for standard and target stimuli using 2 (Age: Y, O) $\times$ 2 (Task: ST, DT) $\times$ 10 (Time: 550–1000 ms at 50 s intervals) mixed ANOVA with age as the between-subject and task and time as within-subject factors.

Target stimuli. There were significant main effects of task [F(1, 43) = 7.18, $p <.01$, $\eta_p^2 = 0.14$; power was greater in DT] and time [F(9, 387) = 6.36, $p <.001$, $\eta_p^2 = 0.13$], and a significant task $\times$ time interaction [F(9, 387) = 3.06, $p <.01$, $\eta_p^2 = 0.07$; DT higher power relative in the 600–700 ms time period]. There were no other significant effects.

Standard stimuli. There was a significant main effect of time [F(9, 387) = 4.18, $p <.001$, $\eta_p^2 = 0.09$] and a significant interaction between age and time [F(9, 387) = 3.03, $p <.05$, $\eta_p^2 = 0.07$; numerically, O had greater power than Y in the 700–800 ms time period, but the means comparisons were not significant according to set criteria].

2.3.3. Visuomanual tracking deviation

The observed patterns of tracking deviation in the motor-only, dual task (standard stimulus) and dual task (target stimulus) conditions can be seen in Fig. 6. The θ and ρ values over the course of the trial period are relative to the values at the latency of the P3b peak. The θ and ρ deviations were analyzed using a 2(Age:Y,O) $\times$ 3(Task: Motor-only, DT standard, DT target) $\times$ 5(Time Delay from P3b peak: 300, 600, 900,
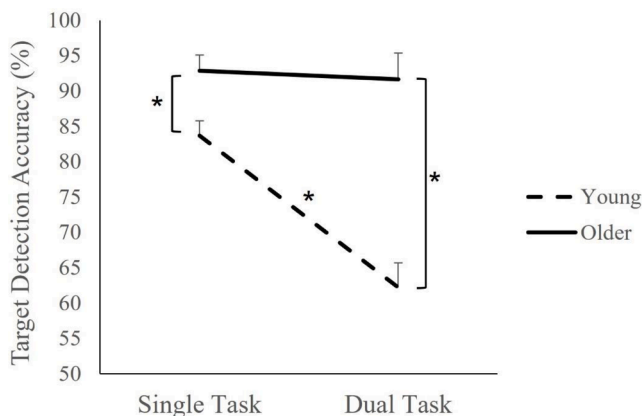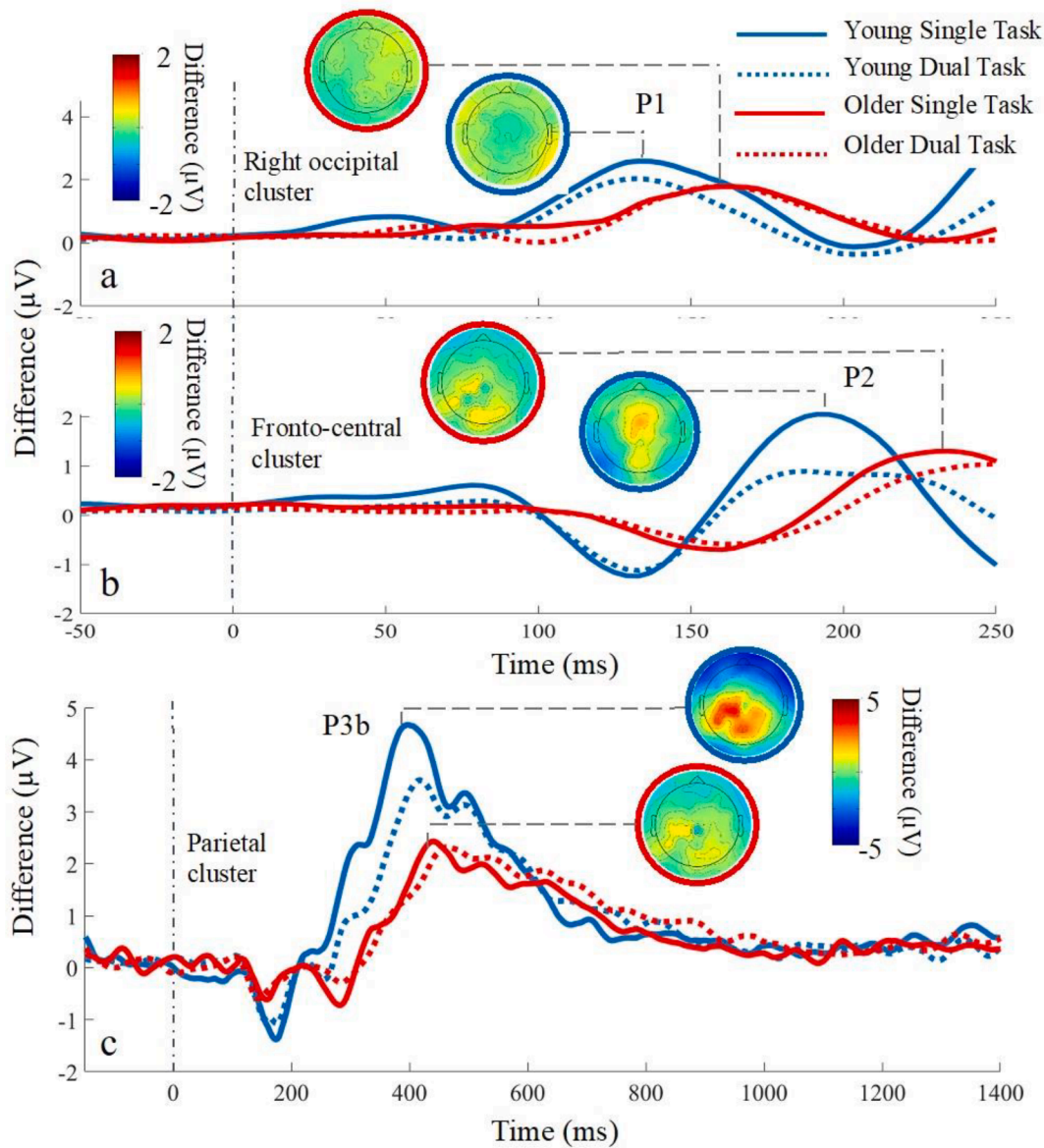
Fig. 2. Accuracy in the oddball task. * marks Bonferroni-corrected significant mean differences.

Fig. 3. Grand average ERP waveforms for target stimuli derived from right occipital (a), fronto-central (b), and parietal (c) electrode clusters, showing, respectively, P1, P2 and P3b components in single and dual task conditions for young and older participants. The corresponding scalp topographies are of difference waves (single-task - dual-task) at the single-task peaks of young and older participants' grand-average P1, P2 and P3.

1200, 1500 ms) mixed ANOVA with age as the between-subject and task and time delay as within-subject factors.

θ Deviation. There were significant interactions between age and time delay [$F(4, 172) = 7.45, p < .01, \eta_p^2 = 0.15$] and between task and time delay [$F(8, 344) = 5.20, p < .01, \eta_p^2 = 0.11$]. The three-way interaction between age, task and time delay was also significant [$F(8, 344) = 5.81, p < .01, \eta_p^2 = 0.12$]. Relative to Y, O produced a positive θ deviation (i.e., their controlled dot went ahead relative to Y) at the time delays of 600 ms and up in the standard-stimulus dual task condition and at delays of 900 ms and up in the target-stimulus dual task condition (Fig. 7). There were no significant deviations from the reference values at any delay in the motor-only condition.

ρ Deviation. There were significant main effects of task [$F(2, 86) = 4.10, p < .05, \eta_p^2 = 0.09$] and time delay [$F(4, 172) = 4.55, p < .01, \eta_p^2 = 0.10$], but pairwise differences were not significant to corrected level. There were no significant deviations from the reference values at any delay in the motor-only condition.

2.3.4. Effects of dual tasking on Spectral power over primary motor cortex

For alpha-band power, we conducted a 2 (Age: Y, O) × 2 (Hemisphere: LH, RH) × 5 (Condition: ST-standard, ST-target, DT-standard, DT-target, tracking-only) mixed ANOVA with age as the between-subject and hemisphere and condition as within-subject factors. There were significant main effects of hemisphere [$F(1, 43) = 28.44, p < .001, \eta_p^2 = 0.40$; LH showed more ERD, i.e., less power] and condition [$F(4, 172) = 22.82, p < .001, \eta_p^2 = 0.35$]. Power was lower (indicating the expected presence of ERD) in the three conditions involving tracking. There were no other significant effects. There were no differences in alpha power over the contralateral motor cortex between tracking in the single and dual task conditions for Y or O.

3. Discussion

The target detection rate of Y reduced when the oddball task was performed concurrently with the visuomanual tracking task (Fig. 2) but this sign of dual task interference was notably absent in O's detection
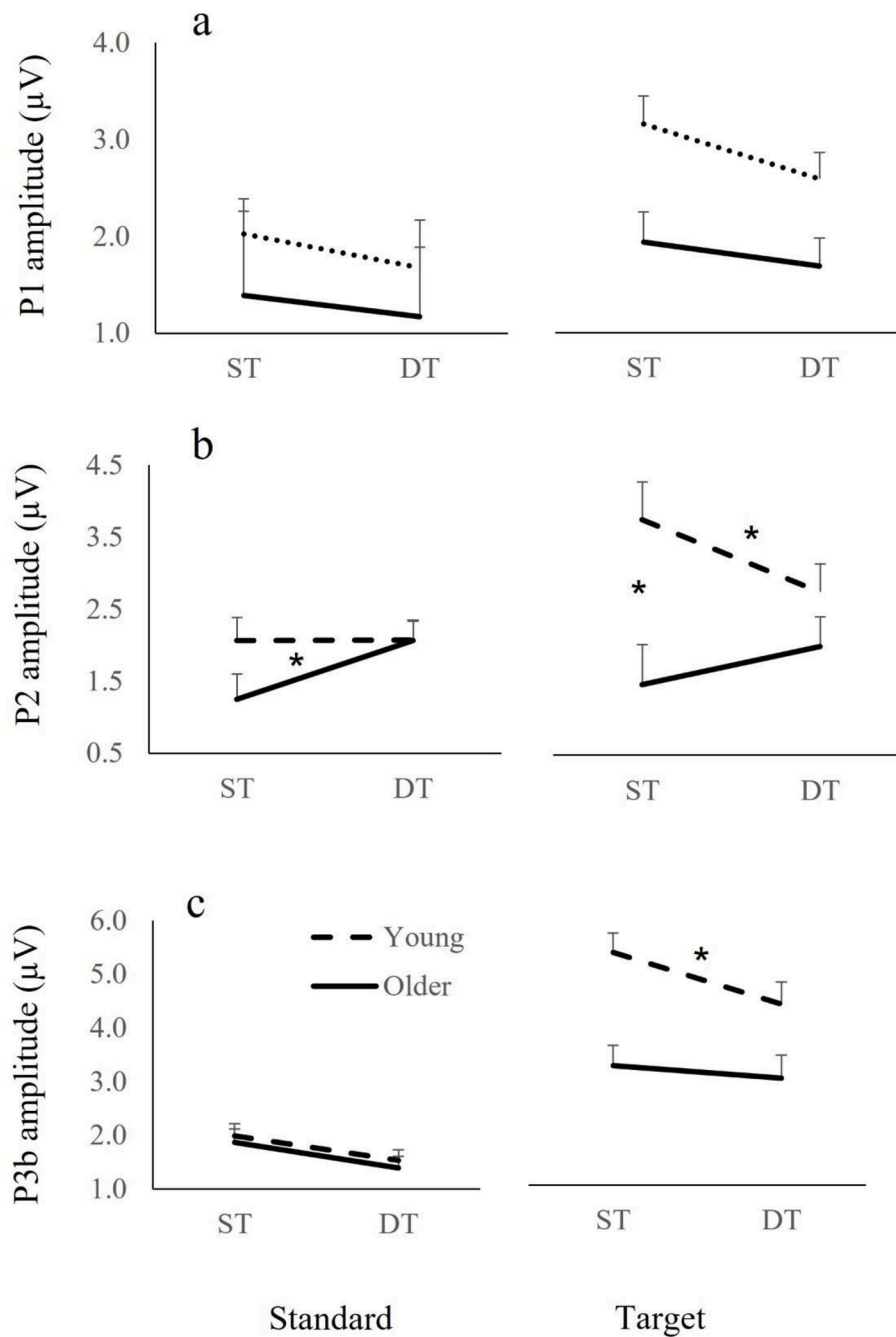
Fig. 4. The effects of task and stimulus type on the P1 (a), P2 (b), and P3b (c) peaks of young and older participants. * marks Bonferroni-corrected significant mean differences.

rate in the dual task condition. O's performance is consistent with prioritization of oddball task performance (despite receiving the same instructions as Y), maintaining in both conditions an accuracy rate not matched by Y even in the single-task condition. This pattern suggests that, faced with the concurrent demands of the tracking task, O did not release cognitive resources (at a cost to performance) in the manner that Y appear to have done. We examine next the extent to which this age-related difference is expressed in the electrophysiological measures.

At ~ 100 ms post stimulus onset, P1 amplitude was greater for the target stimulus, which was expected given its greater contrast. O's P1 amplitude was lower than Y's reflecting a lower level of perceptual resourcing. O also showed less difference in P1 amplitude between the standard and target stimuli than Y, reflecting lower sensitivity to the difference in contrast between the two stimuli. The significant reduction

in P1 amplitude in the dual task condition suggests that performing the tracking task reduced perceptual resourcing of oddball stimulus detection. Note that this effect was not significant when Y were studied alone in Baker et al. 2018, but as the pattern was the same for Y and O (Fig. 4a), we conclude that dual tasking did impact early-stage perceptual processing of the oddball stimulus.

Even though O's P1 amplitude was lower than Y's, O's target detection accuracy was greater than Y's, suggesting that O may have better resourced the top-down categorization/template-matching function represented by P2 amplitude (Kim et al., 2008; Luck, 2014). Indeed, Y and O diverged in the P2 amplitude pattern across task and stimulus conditions (Fig. 4b). In the dual task condition, Y's P2 amplitude to target stimuli reduced, but O's did not. Even for the standard stimuli, O's P2 amplitude increased during dual tasking (whereas Y's did not
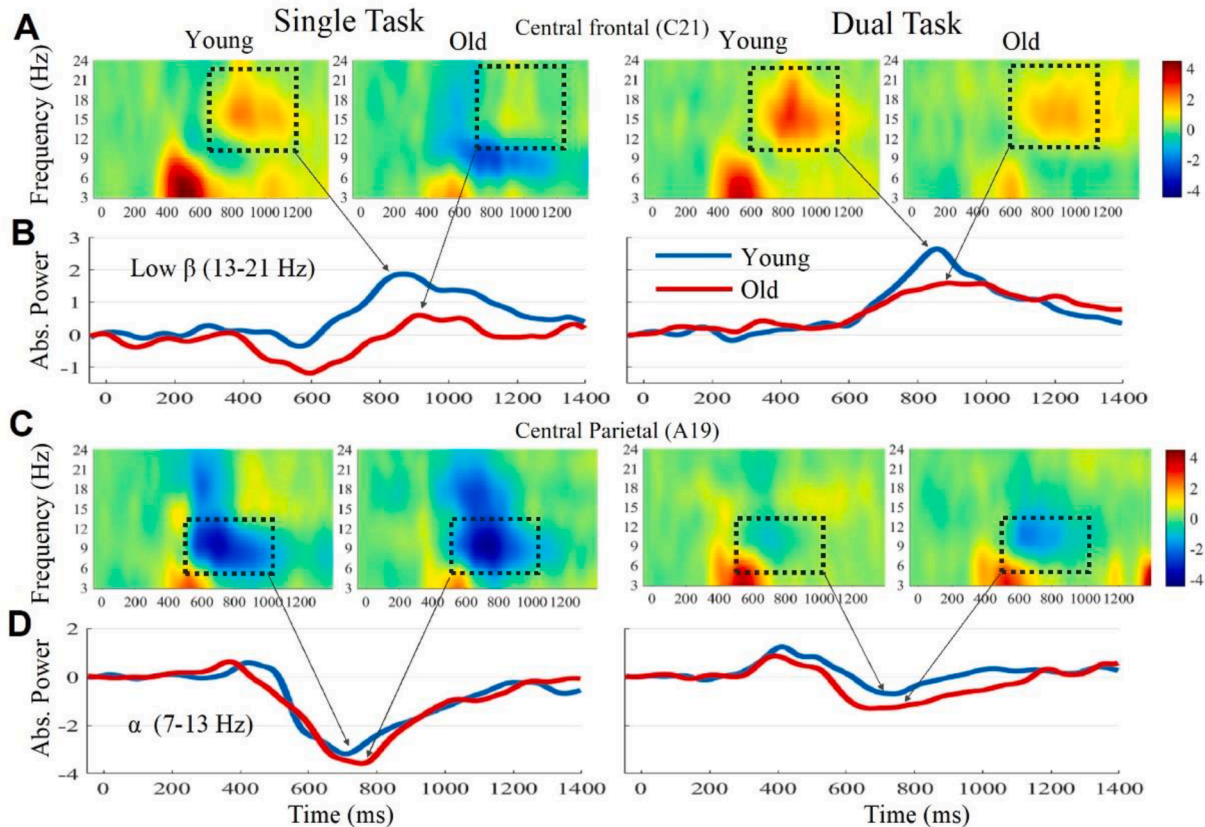
Fig. 5. Grand average time–frequency representation of target trials in single and dual task conditions for young and older participants. Spectral power changes (dB) as a function of time for target stimuli in single and dual-task conditions at frontal electrode C21 (A), frontal beta power time series (B), power changes at parietal electrode A19 (C), and parietal alpha power time series (D).

change). While Y's reduced resourcing (in the case of the target stimuli) in this template-matching stage reflects their reduced accuracy during dual tasking, O's increased resourcing of this process (for both stimulus types) and their greater accuracy suggests that O did not reduce their focus on oddball-stimulus processing even under dual task load. We return to this issue when discussing age-related differences in tracking performance.

In the case of P3b amplitude, which we take to be linked to identifying the stimulus as the target and acknowledging its relevance to the response process (Luck, 2014; Polich, 2007), Y again showed attenuation in the dual task condition (Fig. 4c), reflecting reduced resourcing of this process. This attenuation of P3b amplitude was not significant in O, however. This absence of an amplitude reduction reinforced our conclusion that, unlike Y, O did not reduce cognitive resourcing of the oddball task to accommodate the demands of the concurrent tracking task.

We turn next to the patterns observed in the time–frequency analyses of EEG data. As the target stimulus in the oddball task is rarer than the standard one, it triggers a change in processing that should generate a parietal alpha-band ERD (i.e., power reduction) ~ 400–600 ms post stimulus onset (Sutoh et al., 2000). In both Y and O, the parietal ERD was reduced (i.e., power was higher) during dual tasking for both the standard and target stimuli, indicating dual task interference on the oddball task. In the case of the target stimulus (Fig. 5), O showed greater ERD than Y (i.e., lower parietal alpha-band power). This points to the continuation of O's higher level of attentional resourcing of the oddball task compared to Y.

The impact of dual tasking on working memory load was echoed in the level of frontal beta power observed in the post P3b time period

(Fig. 5 shows the spectra for the target stimulus). Power here was greater in the dual task condition for both Y and O, reflecting the greater WM load relative to the single task condition (Doi et al., 2013; Holtzer et al., 2011; Leone et al., 2017; Meester et al., 2014). Interestingly, O registered higher power than Y in the 700–800 ms time period in the case of the standard stimulus. We did not analyze this, but the late frontal effect (LFE) is a frontal ERP component that occurs in this time frame, at a higher amplitude in O, and is associated with monitoring post memory retrieval (Wolk et al., 2009). It is not clear whether the observed increase in frontal beta power is linked to the LFE. If the increase in frontal beta power is an indication of elevated WM load late in the timeline, it may point to the age-related differences in tracking deviation that we discuss next.

Tracking performance was steady for both Y and O in the motor-only condition (i.e., when they tracked without the concurrent oddball task), but tracking deviation was apparent in the post P3b period in the dual task conditions. Taking the case of target stimuli first, Y showed an angular advance (i.e., positive θ deviation) that peaked around 300 ms after the P3b and reversed thereafter (Figs. 6, 7). O's similar angular advance was not only delayed relative to Y (peaking at around 600 ms post P3b), but also remained at a higher level than Y's late into the epoch. Thus, the effect of dual task pressure resulted in a longer period of tracking inaccuracy in O in the case of the target stimulus. Interestingly, O's tendency to track ahead (in angular terms) following stimulus presentation was evident not only in the case of targets, but also in the case of standard stimuli. O went ahead over most of the latter part of the epoch. Unlike the targets, the standard stimuli did not require a post-identification tallying action (and the EF workload associated with this updating operation). Nevertheless, O's tracking performance
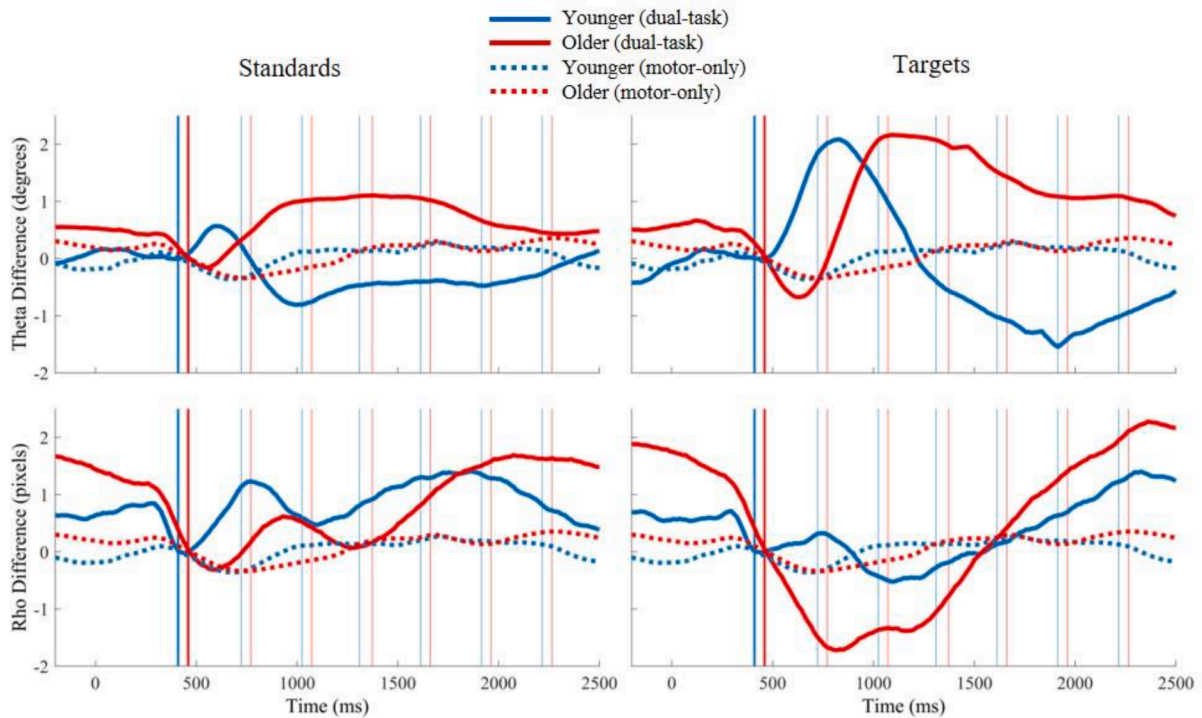
Fig. 6. Grand average epoched θ (degrees) and ρ (pixels) deviations for the motor-only task and dual-task standard and target trials for young and older participants. Data are relativized to the θ and ρ values at the time of the participant group's P3b peak in the dual-task target condition (shown as vertical lines).
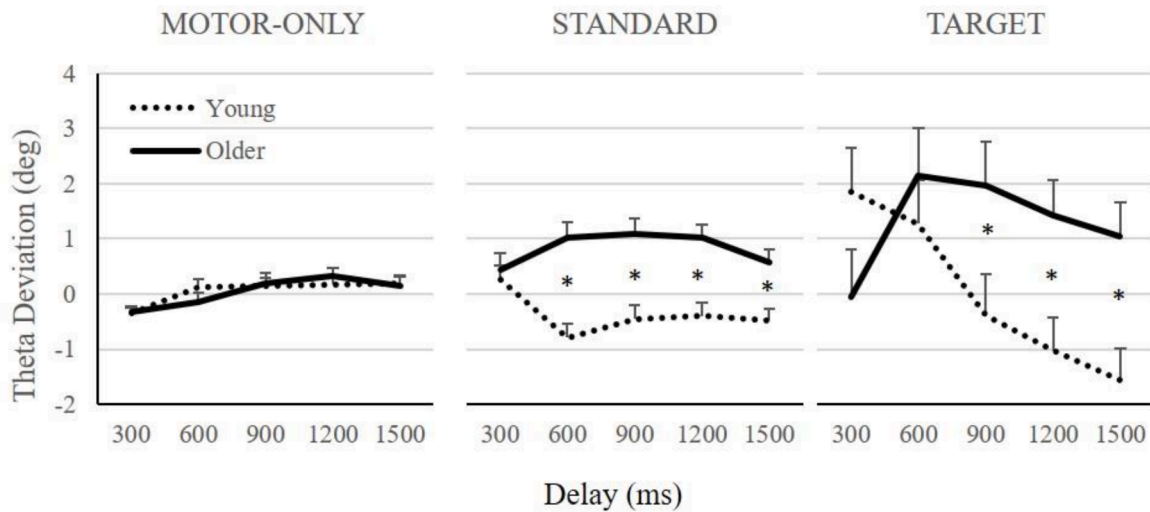

Fig. 7. Results for θ deviation in the motor tracking task. The horizontal axis shows latency from oddball stimulus onset. The motor-only time series is epoched in the same way for illustration.

suggests a draw of resources to the oddball task at the expense of tracking performance. Note, relatedly, O's elevated WM load (as measured by frontal beta power) for both standard and target stimuli, when only the latter required an updating operation. This reinforces the interpretation that, unlike Y, O did not efficiently release resources from the cognitive task even when the stimulus was not a target. This type of cognitive-task prioritization has also been observed in the context of tracking tasks by Corp et al. (2018), who suggested that training O to better attend to motor coordination may be protective during activities with the risk of accidents and injury. This issue requires detailed investigation as evidence suggests that motor performance is in fact better when attention is directed externally to the environmental consequences of action (Chua et al., 2021). This points to the use of

perceptual information to guide motor coordination, which we address next.

There was no evidence in the data suggesting a reduction of motor resourcing during dual tasking by either age group. The tracking-only and dual task conditions involved motor activity whereas the oddball single task did not. Accordingly, the analysis of alpha power over the contralateral motor cortex showed desynchronisation in these conditions of motor activity compared to the oddball single task. However, there was no difference between tracking-only and dual task conditions in either age group. This is consistent with no reduction in motor resourcing due to dual tasking. The dual task impact on tracking performance in both age groups may have occurred in the gathering and utilization of error information rather than motor planning or execution.

Further studies are needed to fully explore this possibility. It is important to note here that the present study was limited in that it required tracking at comfortable speed only. This speed was established at an individual level, with O's speeds ranging 72–104 dps (degrees per second) and Y's ranging 96–144 dps. Thus, the procedure for establishing a comfortable speed also enabled O to perform at a slower speed than Y. There is evidence that motor performance deteriorates more in O than Y when task speed increases (Riviere and Thakor, 1996). It is possible, therefore, that reduction in motor resourcing would be detectable in dual tasks where tracking occurs at faster-than-comfortable speeds.

The key insight achieved through Baker et al.'s (2018) use of the present experimental paradigm with the Y cohort was that the interference between an effortful cognitive task (i.e., one requiring attention and EF resourcing) and a continuous sensorimotor coordination task can be temporally asymmetric. The addition of visuomanual tracking had a negative impact on the attentional resourcing of the oddball task (in the P2-P3 timeframe) but performing the oddball task resulted in tracking deviation only in the post-P3b timeframe, and this only occurred in the case of target stimuli. Baker et al. interpreted this pattern as indicating that it was the executive load of updating the targets tally that affected resourcing of the tracking task. The tracking task's continuous resource demands were adaptively accommodated by reducing resourcing of the attentional components of the oddball task, and by accepting reduced accuracy in the executive task of updating the targets tally. This clarity in the dual task trade-offs was enabled by the choice of a cognitive task with clear functional stages with known electrophysiological correlates, and by pairing it with a visuomotor task whose errors could be continuously measured, and whose speed could not be varied to accommodate the total workload of dual tasking.

As dual task costs are known to be greater in older adults, the purpose of applying the Baker et al. (2018) paradigm to the O cohort was to investigate how the age-accrued cognitive resource limitations affected resource-sharing between these two types of concurrent tasks. Even though both cohorts received identical instructions, and O were able to select their (on average slower) tracking speed in the same manner as Y, O did not demonstrate the adaptive changes shown by Y in terms of reduced resourcing of the oddball task when tracking concurrently. On the contrary, they increased resourcing of the oddball task (e.g., greater P2 amplitude and parietal ERD) when faced with the additional load of concurrent tracking. As a result, O maintained their oddball task accuracy. However, O's tracking deviation in the post-P3b period suffered relative to Y, lasting significantly longer followed a later start. The fact that O also showed a similar pattern of tracking deviation to the standard stimuli (which did not require the EF of updating the targets tally) suggests that O decided to maintain focus on the oddball stimuli at the expense of tracking performance. In this light, it would be useful to contrast Y and O's approach to cognitive-CSC dual tasking as the cognitive task's discrimination and executive workloads are systematically varied. Also, as noted at the outset, aging is associated with complex changes to the P300 complex as more anterior components become prominent in the 300 ms post-stimulus timeframe. Future studies using this paradigm could therefore conduct a broader analysis of the scalp distribution of positivity around this timepoint. This paradigm could also usefully extend to domains beyond visual attention, for example, to tasks requiring effortful linguistic processing (e.g., using the N400 to observe responses to semantic violation).

Previous research on motor-cognitive dual tasking where the motor task involved maintaining the body's balance showed that O tended to follow a posture-first principle, whereby they withdrew resourcing from the cognitive task as the prospect of failure in the balancing task arose. In research on dual tasking with gait, the most common and consistent effect of cognitive task load is to reduce gait speed, which can be interpreted as lowering the motor task's load to accommodate the cognitive task's demands. A reverse pattern of prioritizing cognitive task performance at the expense of motor task performance has also been observed, whereby Parkinson's (Bloem et al., 2001) or stroke patients

(Huitema et al., 2006) prioritized cognitive tasks over gait or balance control, or healthy O participants prioritized their planning of future stepping at the risk of losing their balance (Chapman and Hollands, 2007). The present results obtained in the context of a fine motor control task fall in the latter category. In terms of clarifying the fundamental nature of cognitive-CSC interference, the key feature of the present task arrangement was that it did not offer O the possibility of slowing down the tracking task or accepting an elevated level of tracking error. Faced with a level of load that was not manageable, O may have needed to sequence operations from the two tasks (Buerskens et al., 2016) rather than the adaptive capacity-sharing (Pashler, 1994) that Y appear to have pursued.

As results suggesting prioritization of cognitive and CSC tasks have been found for both gross and fine motor CSCs, the difference between strategic adjustments and operational interference may be a central point of interest. In the present paradigm, even the smallest tracking deviation was visible as error, and the circular tracking trajectory ensured that a change in direction was required at every instant to prevent error from growing. Such strict requirements are rarely applied on balance or gait tasks (for safety reasons if no other), leaving room for general strategic adjustments to the task situation. On the rare occasion that such precise performance requirements have been imposed on balance function, fundamental differences in interference between task types have been uncovered. For example, Barra et al. (2006) tested standing balance in the unstable tandem stance to the point of failure (i. e., participants had to arrest a fall by grabbing a beam) during dual tasking with either spatial or non-spatial tasks of equivalent load. Although studies combining both types of tasks with standing balance had previously found increases in postural sway with increased dual task load, Barra et al's precise task requirement was able to show that the interference between spatial cognitive tasks and balancing is of a more fundamental nature, and that a modulation of postural sway by dual task load is not the same as amplifying the actual risk of balance failure. Only their spatial task was shown to be able to instigate the latter.

The present paradigm of constant speed circular tracking combined with cognitive tasks whose constituent operations are accessible to temporally precise electrophysiological monitoring provides a similar opportunity to uncover precise loci of interference in the case of dual tasking with fine motor tasks. Future studies can test the impact of higher than comfortable tracking speed, the constancy and reliability of perceptual feedback, and the effects of environmental or central perturbation. Barra et al. (2006) noted that the 'posture first' principle can be transgressed if the individual is able to take risks believing that they will be able to arrest a fall. Similar variations in approach no doubt apply in the case of fine motor tasks, some of which can involve high levels of risk and varying possibilities of preventing harmful error. Even with the simplest of oddball contrasts (filled or unfilled circle) and a tracking speed personalized for comfort, the present paradigm was able to show a qualitative difference in Y and O's approach to accommodating the dual task load. It is of significant interest that O prioritized the cognitive over the CSC task. It would be useful to study whether O would prioritize differently if the visuomanual tracking task was controlling a motor vehicle or operating tools or machinery where errors could be dangerous. This would increase the relative cost of failure, but its urgency may not reach the same order as imminent balance failure which generates significant autonomic arousal and instigates reflexive corrective responses.

4. Conclusion

What the present results highlight is that the effects of age-related capacity limits in cognitive or motor functioning may not result simply in incremental amplification of the dual task interaction effects seen in younger adults. The age-related changes may instead lead to a shift in how the dual task demands are approached. It is clear from the present results that O may protect cognitive task performance instead of

balancing resources between tasks like Y do. In previous work on posture and gait control, O have adopted a posture-first principle at the expense of cognitive task performance. Whether this difference in O's approach is determined by demands on gross or fine motor control, or by the potential costs of failure in either, will require further research to elucidate. Failure in gross motor tasks such as balancing or walking can be expensive, but so can de-prioritizing a visuomanual tracking task such as driving a vehicle or operating machinery. It is clear from a range of aging research that both cognitive and sensorimotor functioning gradually decline in later life. How these functional limitations affect strategic choices in resource allocation under different task conditions is the key question regarding the impact of accruing capacity limitations on CSC-cognitive multitasking in older age.

5. Experimental procedure

5.1. Participants

The older participants were 28 self-reportedly right-handed older adults (13 females; mean age = 69.6 yrs, *SD* = 6.9, range: 60–89) who were recruited through the Trent Ageing Panel (of older participants from the Nottinghamshire community) and paid £20 for their participation. These participants also had normal or corrected-to-normal vision and reported a range of regular physical activity. None had any known neurological disorders at the time of participation. The young participants were the same 24 self-reportedly right-handed adults (13 females; mean age = 25.6 yrs, *SD* = 6.13, range: 19–42) recruited from the Nottingham Trent University (NTU) student community who were reported in Baker et al. (2018). All had normal or corrected-to-normal vision, and no history of sensorimotor or cognitive deficits. None was currently taking prescribed medication. These participants were recruited through a research participation scheme for students and received research credits for their involvement. The data reported here for this group are identical to those in Baker et al's (2018) study, except the new tracking deviation analyses using polar coordinates. All participants gave informed consent before the session and were fully debriefed at the end. Ethical approval for this research was obtained from the Nottingham Trent University College of Business, Law and Social Sciences Research Ethics Committee.

5.2. Apparatus and procedure

The participants sat in a comfortable chair with their eyes positioned approximately 60 cm from the center of a 19″ (48.26 cm) diagonal color LCD screen displaying 1600 × 900 pixels at 60 Hz (Fig. 1A). After describing the required tasks and the structure of the recording session, the experimenter obtained written informed consent, and then presented the pursuit tracking configuration task (see below) to establish the participants' comfortable visuomanual tracking speed. The participant was then prepared for EEG data recording using a Biosemi 128-channel ActiveTwo system (Amsterdam, The Netherlands). Electrodes were placed in the Biosemi ABC configuration using a cap fitted to the participant's head. The participant then performed the visuomanual tracking, visual oddball and dual task sessions in a counterbalanced order. Participants were instructed to fixate at the center of the display (fixation cross) at all times for each of the task conditions and to avoid looking at the moving dots.

5.2.1. Motor task configuration

The participants used a Wacom Intuos Pro digitizing tablet and stylus (Saitama, Japan) to pursue a small cyan-colored leading dot (r = 25 pixels) rotating clockwise in a circle (r = 130 pixels; 36 mm) about a fixation cross (Fig. 1). Participants were positioned so that their eyes were approximately 800–850 mm from the fixation cross on the screen, so that the leading dot's track subtended a visual angle of 2.42–2.57 deg with eyes at fixation (Fig. 1A). Note that the ability to split covert attention between spatial locations has been tested at up to 3.5 deg of eccentricity from fixation (e.g., McMains and Somers, 2004). The stylus' position was represented on screen as a black dot (r = 20 pixels), and the participant's task was to position the stylus over the tablet so as to keep the black controlled dot overlaid on the leading cyan dot throughout the trial duration (10 s). Seven trials were presented sequentially in which the angular velocity of the leading dot increased from 84 degrees per second (dps) in the first trial to 168 dps in the seventh trial (in 12 dps increments). The same seven trials were then presented in reverse order. For each trial, the proportion of the final 7 s of trial time during which the two dots overlapped in horizontal (x) and vertical (y) coordinates was calculated. The angular velocity at which a participant produced their third best tracking performance (i.e., the proportion of trial time in which the dots were superimposed) was taken as that participant's comfortable visuomanual tracking speed. The participants' chosen velocities ranged from 96 dps to 144 dps for the young, and from 72 dps to 108 dps for the older participants. The most common comfortable speed was 120 dps for the young and 84 dps for the older participants. In the experimental trials that followed this configuration task, each participant performed the visuomanual tracking task at their comfortable speed.

5.2.2. Visuomanual tracking task

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

5.2.3. Visual oddball task

A sequence of green-shaded (target stimulus) or green-outlined, non-shaded (standard stimulus) circles (r = 100 pixels) were presented, centered on the fixation cross (Fig. 1A). These stimuli were presented for 200 ms, with an ISI of 2500 ms (Fig. 1B). Target and standard stimuli occurred at a ratio of 1:4, and there were 8, 10 or 12 targets presented in each block (the number of trials per block varied between 40 and 60). The participants' task was to mentally count up the number of targets presented in a block and report it via keyboard response once the block had finished. There were 8 blocks of trials each in the single and dual task conditions (yielding a range of 64–96 targets and 256–384 standard stimuli in each task (single and dual). The number of blocks in which the number of targets were counted correctly was recorded.

5.2.4. Dual tasking

The participants performed the visual oddball task and the visuomanual tracking task simultaneously (Fig. 1B). Each of 8 blocks of approximately 120 s (40–60 oddball trials) started with the leading and controlled dots in overlapping position. As the leading dot started moving, and the oddball task got under way, the participants' task was to maintain the positional overlap between the dots while counting the presented targets. The instantaneous coordinates of the controlled and leading dots, the target count, and the EEG data were recorded. Participants were instructed to maintain eye fixation on the cross at the center of the screen for the duration of the task.

5.3. Measures and analyses

5.3.1. Oddball task accuracy

Performance on the oddball task was defined as the proportion of blocks in which participants correctly counted all the target stimuli (up to 12 per block). Accuracy on a given block was reported as either a 1 or a 0, depending on whether they correctly reported the number of presented targets. Overall oddball task performance for each participant for each condition (oddball task and dual task) was calculated as a proportion (%) of correct blocks out of the possible 8 blocks.

5.3.2. EEG data acquisition

EEG data were recorded using 128 Ag/AgCl active pin electrodes at 2.04 KHz and digitised at 24-bit resolution. Data were referenced online using a CMS/DRL feedback loop with online low pass filtering performed in the analogue to digital converter (5th order sinc response with a -3 dB point at 1/5th of the sampling rate). Electrode offsets (difference in μv of each channel from the CMS electrode) were examined after electrode application and readjusted if the absolute value was >20 μV. Digital markers (event triggers) were inserted into the EEG data via a DB25 cable through a USB-Parallel port adapter (Neurospec AG, Switzerland).

5.3.3. EEG data pre-processing and epoching

EEG data were imported and processed using functions from EEGLAB (Delorme and Makeig, 2004). Data were resampled to 256 Hz, high-pass filtered at 1 Hz and low-pass filtered at 50 Hz using a linear finite impulse response filter. Mains interference (50 Hz and 100 Hz harmonic) was derived and removed from each channel using CleanLine (Mullen, 2012). Linear trends were removed from the data by removing the mean of each channel. Noisy channels were identified from datasets by visual inspection for high frequencies and extreme values and then eliminated. Channels with kurtosis over 5 SD from the mean kurtosis of all channels were also removed. EEG epochs were created by extracting data for −150 to 1500 ms around each trigger (oddball stimulus onset). EEG epochs were searched for artefacts and were removed if they contained low frequency drifts and/or high frequency activity considered to be biomechanical. EEG was finally re-referenced to an average of all channels.

5.3.4. Independent components analyses for artefact rejection

Independent Components Analysis (Infomax ICA (Bell and Sejnowski, 1995)) was applied to EEG epochs to identify sources contributing to the observed EEG data. ICA involves the de-mixing of signals measured across the scalp and is able to identify electrical sources that are maximally temporally independent, thus allowing for the analyses of neural functions in source space (as opposed to sensor space). Component properties (time-series, spectra, topography) were examined in order to identify non-brain sources. Ocular components such as blinks and eye movements were identified by low-frequency, non-time-locked fluctuations with strong power concentrated at the front of the scalp. Muscle components were identified by high frequency activity with concentrated activity close to the jaw. Any suspect ocular and muscular components identified during this process were removed from the observed EEG, and data were back-projected onto the electrodes.

5.3.5. Event-related potential (ERP) analyses

The EEG epochs were baseline-corrected by removing the mean of a baseline period (−150 ms to stimulus onset) from the entire epoch. A series of figures displaying grand average scalp topography was produced from 0 to 1000 ms post stimulus-onset in 5 ms intervals. These frames were collated to produce an animation of scalp voltage distribution as a function of time. The spatial concentration of maximum voltage in the time-range 80–120 ms, 180–220 ms, and 380–420 ms were used to determine electrode clusters for the extraction of the P1, P2, and P3 ERP measurements. A virtual electrode technique (Foxe and Simpson, 2002; Rousselet et al., 2010; Baker et al., 2018) was used to generate ERPs consisting of the maximum value over a cluster of electrodes at each time point throughout the EEG epoch. This accounts for individual differences in which electrode presents the maximum response (Rousselet et al., 2010). P1 amplitude was quantified as the maximum (μv) within the 80–120 ms post stimulus period across a right occipital electrode cluster containing B7, B8, B9, A26, A27 and A28 electrodes. P2 amplitude was quantified as the maximum (μv) within the 180–220 ms post stimulus period across a midline fronto-central electrode cluster containing C26, C20, C13, C25, C21 and C12 electrodes. P3b amplitude was quantified as the maximum (μv) within the 300–500

ms post stimulus period across a midline parietal cluster containing A5, A19, A32, A18, A20 and A31 electrodes. P1, P2, and P3b latency were taken as the times (ms) of the respective amplitude maxima.

5.3.6. Time-frequency and fronto-parietal coherence

The newtimef function (EEGLAB) was used to calculate zero-padded FFTs with hanning window tapering in order to observe the power of frequencies as a function of time. For each participant, a matrix was produced containing log power (dB) values of 100 frequencies in the 3–45 Hz range over the −150–1500 ms period of each epoch. Alpha-band and beta-band power were taken as the average of power values over the 7–13 and the 13–21 Hz range, respectively.

5.3.7. Visuomanual tracking deviation analysis

The instantaneous positional difference between the leading and controlled dots in the visuomanual tracking task was represented in polar coordinates (θ, the angle subtended at the center, and ρ, the distance from the center). The θ deviation was set to be negative when the controlled dot fell behind the lead dot (and positive when it got ahead of the leading dot). The ρ deviation was positive when the controlled dot was farther than the leading dot from the center. For the statistical analysis of experimental effects, θ and ρ values at the latency of the P3b peak was taken as the reference, and deviations from the reference were calculated at delays from P3b peak of 300, 600, 900, 1200 and 1500 ms (Fig. 7). In the experimental condition with only the visuomanual tracking task, tracking data were epoched using what would have been the visual oddball task's timeline (except, of course, those stimuli were not shown).

5.3.8. Spectral power over motor cortex

The spectopo function (EEGLAB) was used to compute alpha power spectral density at left hemisphere (D19) and right hemisphere (B22) sites (corresponding to C3 and C4, respectively) during single-task and dual task standard and target (oddball task) trial periods, and during the single-task motor-only trial periods.

5.3.9. Analyses of Variance

For all ANOVAs reported in the results, the significance level for omnibus effects was set to $p = 0.05$, and a Bonferroni correction (0.05/n; n = number of mean comparisons) was applied to post-hoc tests using Fisher's LSD.

CRediT authorship contribution statement

Suvobrata Mitra: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Charlotte Boatman:** Data curation, Investigation, Methodology, Writing – original draft. **Joshua Baker:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft.

References

Albinet, C., Tomporowski, P.D., Beasman, K., 2006. Aging and concurrent task performance: cognitive demand and motor control. Educ. Gerontol. 32, 689–706.

Alperin, B.R., Mott, K.K., Holcomb, P.J., Daffner, K.R., 2014a. Does the age-related "anterior shift" of the P3 reflect an inability to habituate the novelty response? Neurosci. Lett. 577, 6–10.

Alperin, B.R., Mott, K.K., Rentz, D.M., Holcomb, P.J., Daffner, K.R., 2014b. Investigating the age-related "anterior shift" in the scalp distribution of the P3b component using principal component analysis. Psychophysiology 51, 620–633.

Altamura, M., Goldberg, T.E., Elvevåg, B., Holroyd, T., Carver, F.W., Weinberger, D.R., Coppola, R., 2010. Prefrontal cortex modulation during anticipation of working memory demands as revealed by magnetoencephalography. Int. J. Biomed. Imaging 2010, 1–10.

Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, K., Cockburn, J., 2011. Cognitive motor interference while walking: a systematic review and meta-analysis. Neurosci. Biobehav. Rev. 35, 715–728.

Amboni, M., Barone, P., Hausdorff, J.M., 2013. Cognitive contributions to gait and falls: evidence and implications. Mov. Disord. 28, 1520–1533.

Amenedo, E., Diaz, F., 1998. Aging-related changes in processing of non-target and target stimuli during an auditory oddball task. Biol. Psychol. 48 (3), 235–267.

Baddeley, A.D., 2007. Working Memory, Thought, and Action. Oxford Univ. Press, Oxford, UK.

Baker, J., Castro, A., Dunn, A.K., Mitra, S., 2018. Asymmetric interference between cognitive task components and concurrent sensorimotor coordination. J. Neurophysiol. 120 (1), 330–342.

Bangert, A.S., Reuter-Lorenz, P.A., Walsh, C.M., Schachter, A.B., Seidler, E.D., 2010. Bimanual coordination and aging: Neurobehavioral implications. Neuropsychologia 48, 1165–1170.

Barra, J., Bray, A., Sahni, V., Golding, J.F., Gresty, M.A., 2006. Increasing cognitive load with increasing balance challenge: recipe for catastrophe. Exp. Brain Res. 174 (4), 734–745.

Beede, K.E., Kass, S.J., 2006. Engrossed in conversation: the impact of cell phones on simulated driving performance. Accid. Anal. Prev. 38, 415–421.

Bell, A.J., Sejnowski, T.J., 1995. An information-maximization approach to blind separation and blind deconvolution. Neural Comput. 7 (6), 1129–1159.

Beurskens, R., Helmich, I., Rein, R., Bock, O., 2014. Age-related changes in prefrontal activity during walking in dual-task situations: A fNIRS study. Int. J. Psychophysiol. 92 (3), 122–128.

Bloem, B.R., Valkenburg, V.V., Slabbekoorn, M., Willemsen, M.D., 2001. The Multiple Tasks Test: development and normal strategies. Gait Posture 14, 191–202.

Bock, O., 2005. Components of sensorimotor adaptation in young and elderly subjects. Exp Brian Res 160 (2), 259–263.

Boisgontier M.P., Beets I.A.M., Duysens J., Nieuwboer A., Krampe R.T., Swinnen S.P. (2013). Age-related differences in attentional cost associated with postural dual tasks: Increased recruitment of generic cognitive resources in older adults. *Neurosci. Biobehav. Rev.* 37(8): 1824-1837.

Chapman, G.J., Hollands, M.A., 2007. Evidence that older adult fallers prioritise the planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. Gait Posture 26 (1), 59–67.

Chua, L.-K., Jimenez-Diaz, J., Lewthwaite, R., Kim, T., Wulf, G., 2021. Superiority of external attentional focus for motor performance and learning: Systematic reviews and meta-analyses. Psychol. Bull. 147 (6), 618–645.

Cid-Fernández, S., Lindin, M., Diaz, F., 2014. Effects of aging and involuntary capture of attention on event-related potentials associated with the processing of and the response to a target stimulus. Front. Hum. Neurosci. https://doi.org/10.3389/fnhum.2014.00745.

Cid-Fernández, S., Lindin, M., Diaz, F., 2016. Information processing becomes slower and predominantly serial in aging: Characterization of response-related brain potentials in an auditory–visual distraction–attention task. Biol. Psychol. 113, 12–23.

Corbetta, M., Shulman, G.L., 2002. Control of goal-directed and stimulus-driven attention in the brain. Nat. Rev. Neurosci. 3 (3), 201–215.

Corp, D.T., Youssef, G.J., Clark, R.A., Gomes-Osman, J., Yücel, M.A., Oldham, S.J., Aldraiwiesh, S., Rice, J., Pascual-Leone, A., Rogers, M.A., 2018. Reduced motor cortex inhibition and a 'cognitive first' prioritisation strategy for older adults during dual-tasking. Exp. Gerontol. 113, 95–105.

Czigler, I., Pató, L., Poszet, E., Balázs, L., 2006. Age and novelty: Event-related potentials to visual stimuli within an auditory oddball—visual detection task. Int. J. Psychophysiol. 62 (3), 290–299.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods 134, 9–21.

Doi, T., Makizako, H., Shimada, H., Park, H., Tsutsumimoto, K., Uemura, K., Suzuki, T., 2013. Brain activation during dual-task walking and executive function among older adults with mild cognitive impairment: a fNIRS study. Aging Clin. Exp. Res. 25, 539–544.

Dubost, V., Kressig, R.W., Gonthier, R., Herrmann, F.R., Aminian, K., Najafi, B., Beauchet, O., 2006. Relationships between dual-task related changes in stride velocity and stride time variability in healthy older adults. Hum. Mov. Sci. 25 (3), 372–382.

Fabiani, M., Friedman, D., 1995. Changes in brain activity patterns in aging: The novelty oddball. Psychophysiology 32 (6), 579–594.

Fjell, A., Walhovd, K., 2001. P300 and neuropsychological tests as measures of aging: Scalp topography and cognitive changes. Brain Topogr. 14 (1), 25–40.

Fling, B.W., Kwak, Y., Peltier, S.J., Seidler, R.D., 2012. Differential relationships between transcallosal structural and functional connectivity in young and older adults. Neurobiol. Aging 33 (10), 2521–2526.

Foxe, J.J., Simpson, G.V., 2002. Flow of activation from V1 to frontal cortex in humans. A framework for defining "early" visual processing. Exp. Brain Res. 142, 139–150.

Fraizer, E.V., Mitra, S., 2008. Methodological and interpretive issues in posture-cognition dual-tasking in upright stance. Gait Posture 27, 271–279.

Friedman, D., Kazmerski, V., Cycowicz, Y., 1998. Effects of aging on the novelty P3 during attend and ignore oddball tasks. Psychophysiology 35 (5), 508–520.

Gazes, Y., Rakitin, B.C., et al., 2010. Performance degradation and altered cerebralactivation during dual performance: evidence for a bottom-up attentional system. Behav. Brain Res. 210 (2), 229–239.

Gazzaley, A., D'Esposito, M., 2007. Top-down modulation and normal aging. Ann. N. Y. Acad. Sci. 1097, 67–83.

Geerligs, L., Maurits, N.M., Renken, R.J., Lorist, M.M., 2014. Reduced specificity of functional connectivity in the aging brain during task performance. Hum. Brain Mapp. 35 (1), 319–330.

Guillery, E., Mouraux, A., Thonnard, J.-L., van Beers, R.J., 2013. Cognitive-motor interference while grasping, lifting and holding objects. PLoS ONE 8 (11), e80125. https://doi.org/10.1371/journal.pone.0080125.

Güntekin, B., Basar, E., 2010. A new interpretation of P300 responses upon analysis of coherences. Cogn. Neurodyn. 4, 107–118.

Hahn, M., Wild-Wall, N., Falkenstein, M., 2011. Age-related differences in performance and stimulus processing in dual task situation. Brain Res. 1414, 66–76.

Haigney, D.E., Taylor, R.G., Westerman, S.J., 2000. Concurrent mobile (cellular) phone use and driving performance: task demand characteristics and compensatory processes. Transp. Res. Part F Traffic Psychol. Behav. 3, 113–121.

Hasher, L., Zacks, R.T., 1988. Working memory, comprehension and aging: a review and a new view. In: Bower, G.H. (Ed.), The Psychology of Learning and Motivation. Academic Press, New York, NY, pp. 193–225.

Hocherman, S., Moont, R., Schwartz, M., 2004. Recruitment of attentional resources during visuomotor tracking: Effects of Parkinson's disease and age. Cogn. Brain Res. 21 (1), 77–86.

Holtzer, R., Mahoney, J.R., Izzetoglu, M., Izzetoglu, K., Onaral, B., Verghese, J., 2011. fNIRS study of walking and walking while talking in young and old individuals. J. Gerontol. A Biol. Sci. Med. Sci. 66, 879–887.

Huitema, R.B., Brouwer, W.H., Hof, A.L., Dekker, R., Mulder, T., Postema, K., 2006. Walking trajectory in neglect patients. Gait Posture 23, 200–205.

IJmker T, Lamoth CJ, 2012. Gait and cognition: the relationship between gait stability and variability with executive function in persons with and without dementia. Gait Posture 35, 126–130.

Johannes, S., Münte, T.F., Heinze, H.J., Mangun, G.R., 1995. Luminance and spatial attention effects on early visual processing. Brain Res. Cogn. Brain Res. 2, 189–205.

Johannsen, L., Li, K.Z.H., Chechlacz, M., Bibi, A., Kourtzi, Z., Wing, A.M., 2013. Functional neuroimaging of the interference between working memory and the control of periodic ankle movement timing. Neuropsychologia 51, 2142–2153.

Kaufman, D.A.S., Keither, C.M., Perlstein, M., 2016. Orbitofrontal cortex and the early processing of visual novelty in healthy aging. Front. Aging Neurosci. https://doi.org/10.3389/fnagi.2016.00101.

Kim, K.H., Kim, J.H., Yoon, J., Jung, K.Y., 2008. Influence of task difficulty on the features of event-related potential during visual oddball task. Neurosci. Lett. 445, 179–183.

Leone, C., Feys, P., Moumdjian, L., D'Amico, E., Zappia, M., Patti, F., 2017. Cognitive-motor dual-task interference: a systematic review of neural correlates. Neurosci. Biobehav. Rev. 75, 348–360.

Li, K.Z., Lindenberger, U., 2002. Relations between aging sensory/sensorimotor and cognitive functions. Neurosci. Biobehav. Rev. 26, 777–783.

Lindenberger, U., Marsiske, M., Baltes, P.B., 2000. Memorizing while walking: Increase in dual-task costs from young adulthood to old age. Psychol. Aging 15 (3), 417–436.

Lion, L., Spada, R.S., Bosser, G., Gauchard, G.C., Anello, G., Bosco, P., Calabrese, S., Iero, A., Stella, G., Elia, M., Perrin, P.P., 2014. 'Posture first' principle when balance is challenged in elderly people. Int. J. Neurosci. 124 (8), 558–566.

Liston, M.B., Bergmann, J.H., Keating, N., Green, D.A., Pavlou, M., 2014. Postural prioritization is differentially altered in healthy older compared to younger adults during visual and auditory coded spatial multitasking. Gait Posture 39 (1), 198–204.

Luck, S., 2014. An Introduction to the Event-Related Potential Technique. MIT Press, Cambridge, MA.

Mac-Auliffe D., Chatard B., Petton M., Croize A.-C., Sipp F., Bontemps B., Gannerie A., Bertrand O., Rhelms S., Kahane P., Lachaux J.-P. The dual-task cost is due to neural interferences disrupting the optimal spatio-temporal dynamics of the competing tasks. Front. Behav. Neurosci. 15: 640178. doi: 10.3389/fnbeh.2021.640178.

McMains, S.A., Somers, D.C., 2004. Multiple spotlights of attentional selection in human visual cortex. Neuron 42, 677–686.

Meester, D., Al-Yahya, E., Dawes, H., Martin-Fagg, P., Piñon, C., 2014. Associations between prefrontal cortex activation and H-reflex modulation during dual task gait. Front. Hum. Neurosci. 8, 78.

Miyake, A., Friedman, N.P., 2012. The nature and organization of individual differences in executive functions: four general conclusions. Curr. Dir. Psychol. Sci. 21, 8–14.

Mullen T. *CleanLine EEGLAB Plugin*. San Diego, CA: Neuroimaging Informatics Tools and Resources Clearinghouse (NITRC), 2012.

Nijboer, M., Borst, J.P., van Rijn, H., Taatgen, N.A., 2016. Driving and multitasking: the good, the bad, and the dangerous. Front. Psychol. 7, 1718.

O'Connell R.G., Balsters J.H., Kilcullen S.M., Campbell W., Bokde A.W., Lai R., et al. (2012). A simultaneous ERP/fMRI investigation of the P300 aging effect. *Neurobiol. Aging* 33(10): 2448-2461.

Paitel, E.R., Nielson, K.A., 2021. Temporal dynamics of event-related potentials during inhibitory control characterize age-related neural compensation. Symmetry 13, 2323.

Papegaaij, S., Hortobágyi, T., Godde, B., Kaan, W.A., Erhard, P., Voelcker-Rehage, C., 2017. Neural correlates of motor-cognitive dual-tasking in young and old adults. PLoS ONE 12 (12), e0189025. https://doi.org/10.1371/journal.pone.0189025.

Pashler, H., 1994. Dual-task interference in simple tasks. Psychol. Bull. 116 (2), 220–244.

Pesonen, M., Hämäläinen, H., Krause, C.M., 2007. Brain oscillatory 4–30 Hz responses during a visual n-back memory task with varying memory load. Brain Res. 1138 (1), 171–177.

Pfefferbaum, A., Wenegrat, B.G., Ford, J.M., Roth, W.T., Kopell, B.S., 1984. Clinical application of the P3 component of event-related potentials. II. Dementia, depression and schizophrenia. Electroencephalogr. Clin. Neurophysiol. 59, 104–124.

Pfurtscheller, G., Lopes da Silva, F.H., 1999. Event-related EEG/MEG synchronization and desynchronization: basic principles. Clin. Neurophysiol. 110, 1842–1857.

Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. Clin. Neurophysiol. 118, 2128–2148.

Recarte, M.A., Nunes, L.M., 2003. Mental workload while driving: effects on visual search, discrimination, and decision making. J. Exp. Psychol. Appl. 9, 119–137.

Remy, F., Wenderoth, N., et al., 2010. Dual-task interference during initial learning of a new motor task results from competition for the same brain areas. Neuropsychologia 48 (9), 2517–2527.

Riviere, C.N., Thakor, N.V., 1996. Effects of age and disability on tracking tasks with a computer mouse: Accuracy and linearity. J. Rehabil. Res. Dev. 33 (1), 6–15.

Rousselet, G.A., Gaspar, C.M., Pernet, C.R., Husk, J.S., Bennett, P.J., Sekuler, A.B., 2010. Healthy aging delays scalp EEG sensitivity to noise in a face discrimination task. Front. Psychol. 1, 19.

Rubenstein L.Z. (2006). Falls in older people: epidemiology, risk factors and strategies for prevention. *Age Ageing* 35, *Suppl* 2: ii37–ii41.

Sadaghiani, S., Scheeringa, R., Lehongre, K., Morillon, B., Giraud, A.L., D'Esposito, M., Kleinschmidt, A., 2012. Alpha-Band phase synchrony is related to activity in the fronto-parietal adaptive control network. J. Neurosci. 32, 14305–14310.

Saliasi E., Geerligs L., Lorist M.M., Maurits N.M. (2013). The relationship between P3 amplitude and working memory performance differs in young and older adults. PLoS ONE 8(5): e63701.

Sallard, E., Spierer, L., Ludwig, C., Deiber, M.-P., Barral, J., 2014. Age-related changes in the bimanual advantage and in brain oscillatory activity during tapping movements suggest a decline in processing sensory reafference. Exp. Brain Res. 232 (2), 469–479.

Sauseng, P., Klimesch, W., Freunberger, R., Pecherstorfer, T., Hanslmayr, S., Doppelmayr, M., 2006. Relevance of EEG alpha and theta oscillations during task switching. Exp. Brain Res. 170, 295–301.

Serbruyns, L., Gooijers, J., Caeyenberghs, K., Meesen, R.L., Cuypers, K., Sisti, H.M., Swinnen, S.P., 2015. Bimanual motor deficits in older adults predicted by diffusion tensor imaging metrics of corpus callosum subregions. Brain Struct. Funct. 220 (1), 273–290.

Shetty, A.K., Shankar, M.S.V., Annamalai, N., 2014. Bimanual coordination: influence of age and gender. J. Clin. Diagn. Res. 8 (2), 15–16.

Skoura, X., Papaxanthis, C., Vinter, A., Pozzo, T., 2005. Mentally represented motor actions in normal aging: I. Age effects on the temporal features of overt and covert execution of actions. Behav. Brain Res. 165 (2), 229–239.

Spencer, K.M., Polich, J., 1999. Poststimulus EEG spectral analysis and P300: attention, task and probability. Psychophysiology 36, 220–232.

Springer, S., Giladi, N., Peretz, C., Yogev, G., Simon, E.S., Hausdorff, J.M., 2006. Dual-tasking effects on gait variability: the role of aging, falls, and executive function. Mov. Disord. 21, 950–957.

Strayer, D.L., Johnston, W.A., 2001. Driven to distraction: dual-task studies of simulated driving and conversing on a cellular telephone. Psychol. Sci. 12, 462–466.

Summers, J.J., Lewis, J., Fujiyama, H., 2010. Aging effects on event and emergent timing in bimanual coordination. Hum. Mov. Sci. 29 (5), 820–830.

Sutoh, T., Yabe, H., Sato, Y., Hiruma, T., Kaneko, S., 2000. Event-related desynchronization during an auditory oddball task. Clin. Neurophysiol. 111, 858–862.

Van Impe A., Coxon J.P., Goble D.J., Wenderoth N., Swinnen S.P. (2011). Age-related changes in brain activation underlying single- and dual-task performance: Visuomanual drawing and mental arithmetic. *Neuropsychologia* 49(9): 2400-2409.

Van Ruitenbeek, P., Serbruyns, L., Solesio-Jofre, E., Meesan, R., Cuypers, K., Swinnen, S. P., 2017. Cortical grey matter content is associated with both age and bimanual performance, but is not observed to mediate age-related behavioural decline. Brain Struct. Funct. 222 (1), 437–448.

van Schouwenburg, M.R., Zanto, T.P., Gazzaley, A., 2017. Spatial attention and the effects of frontoparietal alpha band stimulation. Front. Hum. Neurosci. 10, 658.

Vaportzis, E., Georgiou-Karistianis, N., Stout, J.C., 2014. Age and task difficulty differences in dual tasking using circle tracing and serial subtraction tasks. Aging Clin. Exp. Res. 26 (2), 201–211.

Voelcker-Rehage, C., Stronge, A.J., Alberts, J.L., 2006. Age-related differences in working memory and force control under dual-task conditions. Neuropsychol. Dev. Cogn. B Aging Neuropsychol. Cogn. 13, 366–384.

Wolk, D.A., Sen N.M., Chong H., Riis J.L., McGinnis S.M., Holcomb P.J., Daffner K.R. (2009). ERP correlates of item recognition memory: Effects of age and performance. Brain Res. 1250: 218-231.

Woollacott, M., Shumway-Cook, A., 2002. Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 16, 1–14.

Yogev-Seligmann, G., Hausdorff, J.M., Giladi, N., 2008. The role of executive function and attention in gait. Mov. Disord. 23, 329–342.