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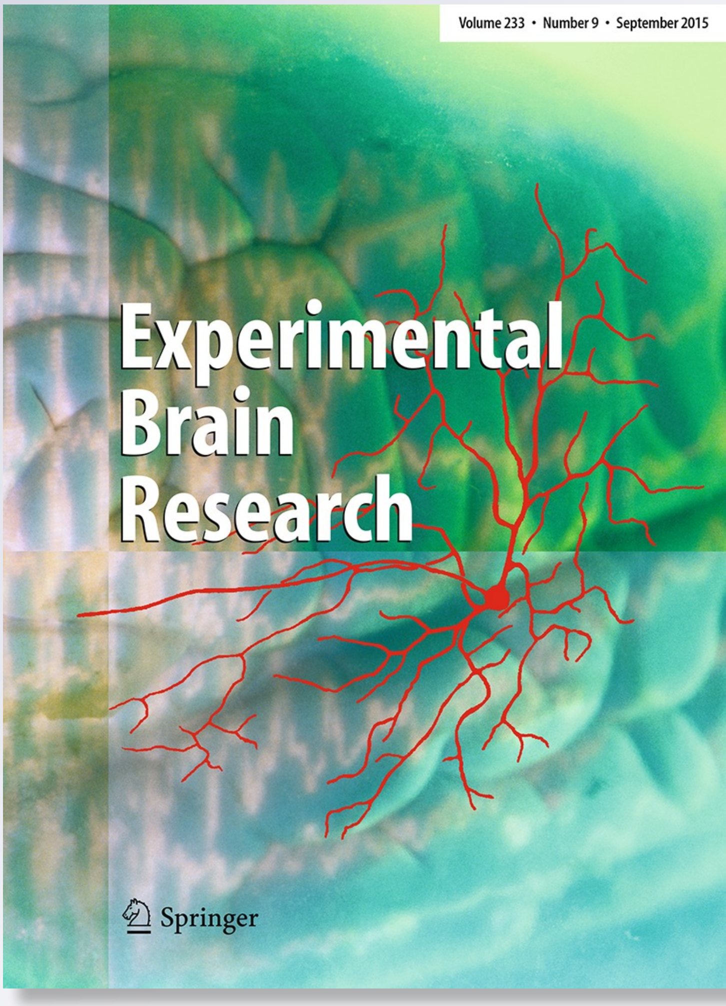

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RESEARCH ARTICLE

Allocation of attention and dual-task effects on upper and lower limb task performance in healthy young adults

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Abstract Many daily activities require separate tasks of the arms and legs to be performed together, as in driving where one foot controls the accelerator, one arm steers, and the other arm and foot shift gears and clutch. Strategies and underlying mechanisms for attention allocation and task prioritization have been explored in standing and walking while performing a manual or cognitive task. These studies reveal a task-related strategy that often, but not always, prioritizes the lower limb task of walking. However, in the absence of locomotion and gait-related postural control, as in sitting, multi-limb dual-task strategies are largely unexplored. Therefore, to characterize dual-task interference of arm and leg tasks during a driving-like activity, seated participants were assessed for the interference effect on hand velocity and movement time of a three-phase reach task and on the error in tracking of a foot-pedal ramp-tracking task. We found that the dual-task cost to reaching shown as decreases in reach performance differed among the three phases, that the cost to foot-pedal tracking also differed by phase, and that the between-task trade-off and prioritization strategy varied between the steep and gradual tracking ramps. Therefore, we propose that attention to concurrent reaching and foot-pedal tracking was flexibly allocated based on phase of the tasks.

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Introduction

Daily activities frequently require using the arms and legs to perform different tasks at the same time such as when driving or walking while carrying an object. Such dual-task activities require greater attention than single-task activities even in healthy young adults (Laessoe et al. 2008; Stutts et al. 2005). Driving is a complex motor and cognitive task performed by over 200 million people in the USA (Federal Highway Administration 2012). Potentially, all four limbs can be simultaneously involved in driving: One or both feet may be used to brake, accelerate, or press the clutch, while one hand may be steering and the other reaching to grab a cup, turn the radio knob, shift gears, adjust mirrors, or roll the window up or down. Indeed, engaging in visual–manual actions related to using portable devices, such as reaching for a phone, dialing, and texting, tripled the risk of getting into a crash (Fitch et al. 2013). Thus, understanding the interaction of information processing demands and multi-limb control is critical for identifying principles of cognitive motor control and for addressing issues of safety and mobility.

Much of what is known about dual-task attention and multi-limb control comes from studies of dual-task interference on postural control in standing and walking, which suggest an important role of cognitive executive function and attention in walking (Lajoie et al. 1993; Woollacott and Shumway-Cook 2002; Yogev-Seligmann et al. 2008). When healthy adults walk while handling an object, the lower limb task performance (walking) is largely maintained, but the manual task performance declines (Plummer-D'Amato et al. 2012), possibly due to the prioritization of balance, known as the "posture first" strategy (Bloem et al. 2001). However, posture first is not an invariant strategy (Kelly et al. 2013; Shumway-Cook et al. 1997; Yogev-Seligmann et al. 2012), suggesting that task prioritization is dynamic and related to aspects of the task, the setting, and the conditions of the performer. When applied to seated multi-limb tasks like driving, task prioritization, and attention allocation strategies among limbs are not clearly understood.

Another consideration of multi-limb control in dual-task walking is that the upper limb task is directly impacted by the gait events of the lower limb task. The fluctuating inertial forces generated with each step evoke anticipatory changes in grasp control in healthy young and older adults (Diermayr et al. 2011; Gysin et al. 2008). When seated and in the absence of cyclic movements as in driving, however, the upper and lower limb tasks are largely uncoupled from the locomotor and balance concerns inherent in walking.

The aim of the present study was to characterize the dual-task interference effects and attention allocation in a novel multi-limb seated task under two conditions of task difficulty. Thus, the upper and lower limb tasks were performed in the absence of locomotion and without the influence of gait-related balance control mechanisms. During single- and dual-task conditions, we measured the kinematics of a three-phase reaching task that mimics behaviors frequently used by drivers (Stutts et al. 2005). We likewise measured the accuracy of a foot-pedal, ramp-tracking task that mimics control of the accelerator pedal while driving. If there was a limitation or degree of shared capacity for processing information of both tasks, there would be a decline in reaching velocity and tracking error relative to each single-task performance, the dual-task effect (negative DTE, cost). Furthermore, if attention was allocated to prioritize the lower limb task, then we expected to see a greater relative cost to the foot-pedal, ramp-tracking task compared with the reaching task. However, if minimizing the postural control issue by using a seated task resulted in allocating attention to prioritize the upper limb task, then we expected to see a greater relative cost (more negative DTEs) to reaching compared with the foot-pedal tracking task.

Methods

Participants

Participants were twelve right-handed adults (mean age 27.6 ± 4.0 years, 6 females), who were healthy and without orthopedic, neurological, or cognitive conditions. All participants provided informed consent before study participation, and the study was approved by the local institutional review board and in accordance with the Declaration of Helsinki.

Experimental apparatus

The upper limb task object was a standard compact disk (12 cm diameter), which was positioned on a table at participant's midline and at a distance that was equal to the distance from the participant's acromion to the third metacarpophalangeal joint. This distance allowed the participant a full arm's reach without a forward lean of the trunk and started and ended with the hand on the table 15 cm directly in front of the participant. The CD was to be placed 30 cm to the right of the start/end location marked by a 3-cm square piece of tape. Hand position during the three-phase reach task (grasp–place–return) was measured by an electromagnetic sensor placed on the dorsum of the participant's hand (FASTRAK, Polhemus, Vermont) and was recorded and stored for off-line export and analysis with Spike2 software (Cambridge, UK).

For the lower limb task, a custom-made hinged pedal (12 cm × 20 cm surface; 3.4 N return mechanism force) recorded angular pedal position. Target traces presented for the foot-pedal, ramp-tracking task were one of the two ramp shapes (gradual ramp of 0.7°/s incline and decline each for 6.5 s with intervening 5 s level; steep ramp of 6.5°/s incline and decline each for 1.7 s with intervening 5 s level, Fig. 1) displayed on a 22-in. computer monitor. The pedal position and the target traces scrolled to the center of the computer screen and stayed there so they would be in front of the participant at eye level and approximately 80 cm away, which allowed the participant to centrally track the target visually.

Foot-pedal position data, the auditory cues to reach, and the target traces were acquired and controlled through CED Power 1401 MK2 (Cambridge, UK) using custom-written programs in Spike2. Data were analyzed off-line using Labview 7.1 (National Instrument, Texas).

Protocol

Participants were seated and instructed in the overall dual-task paradigm procedure for performing the two tasks (three-phase reaching and foot-pedal, ramp-tracking), both separately and simultaneously. The upper and lower limb single-task conditions were counterbalanced across participants.

Upper limb single-task

For the three-phase reaching task, on hearing an auditory cue, participants were instructed to "pick up the CD, place it here (target indicated by investigator) and return to the

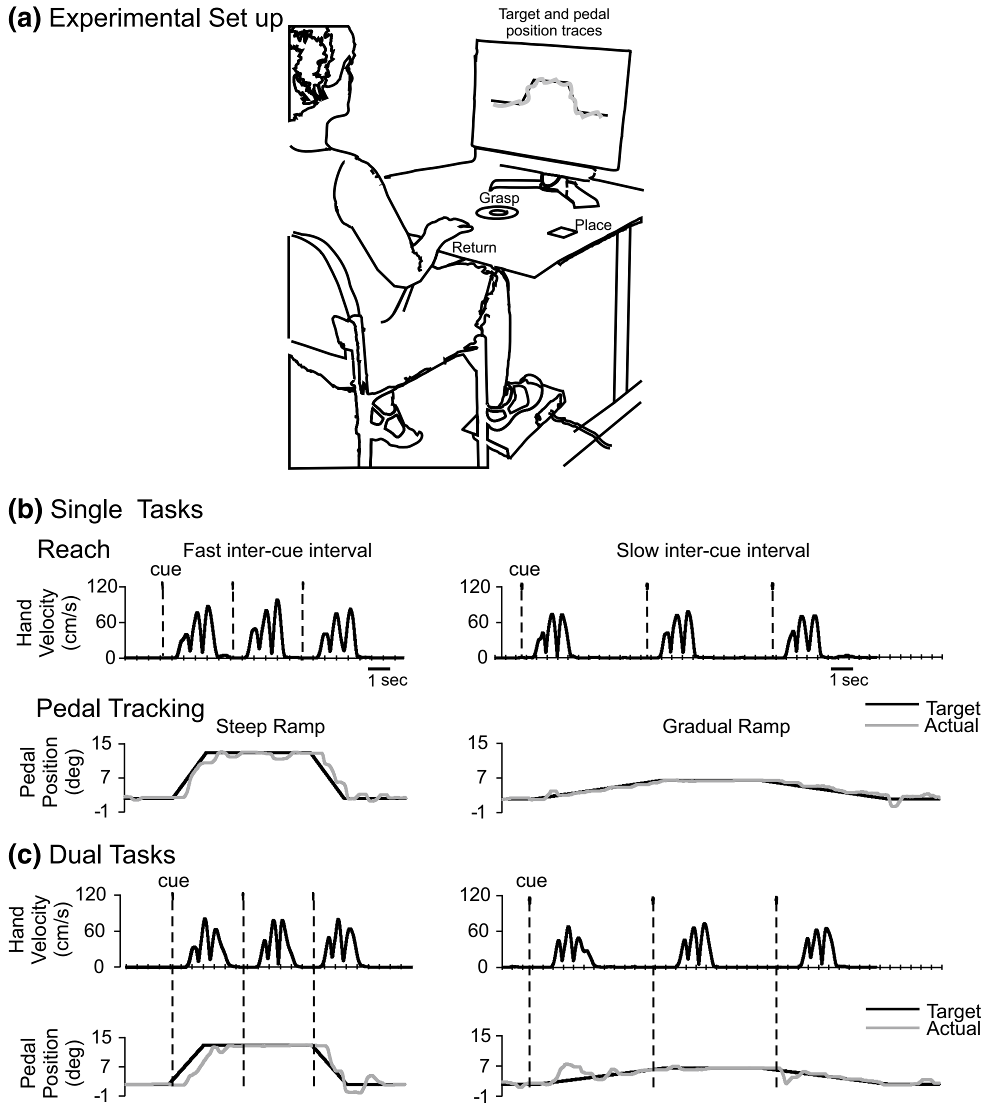

Fig. 1 **a** Experimental setup and representative traces of hand velocity profiles and foot-pedal target (*dark*) and actual position (*light*) traces for a single participant. Panel **b** depicts a single-task reach trial (*upper trace*) and foot-pedal tracking task (*lower traces*) during the steep ramp and fast inter-cue interval condition (*left side*) and during the gradual ramp and slow inter-cue interval condition (*right side*). Panel **c** depicts a dual-task trial using the same conventions as panel (**b**). Vertical dashed lines represent the auditory cues to reach

start empty-handed" in outlining the grasp, place, and return phases of the task, with no instructions specific to speed. Neither instructions nor consequences for accuracy were given for object placement. Inter-cue intervals of different durations for the reach task could impact dual-task interference by allowing participants more processing time. Thus, auditory cues for the reaching task were given with inter-cue intervals of 3 s (fast) and 6 s (slow), which were evenly distributed during the dual-task conditions across the duration of the steep and gradual ramps, respectively (Fig. 1). Participants were allowed a few practice trials using inter-cue intervals that were 1–2 s different than those used in the actual trial. The single-task condition consisted of a block of three reaches performed sequentially with the predetermined inter-cue intervals. Participants performed a total of ten blocks, five with fast and five with slow inter-cue intervals, counterbalanced across blocks.

Lower limb single-task

For the lower limb task, participants were instructed to track the moving target "as closely as possible" by pressing the pedal with their right foot so that the position trace went up when the pedal was pressed (more plantar flexion) and went down when the pedal was released (dorsiflexion). Participants were allowed a few practice trials to learn how to control the pedal using free-form and step-wise target trace patterns rather than the ramp shapes used in the actual trials. The scrolling target trace formed a series of five ramps with 5 s inter-ramp intervals (a block), each having gradual and steep ramps, which were randomly selected and counterbalanced across blocks. In the lower limb single-task condition, participants performed two blocks of five ramps.

Dual-task

Dual-task conditions always followed single-task conditions to give participants experience in each task prior to combining them. For dual-task conditions, participants were instructed to perform the three-phase reaching and foot-pedal, ramp-tracking tasks at the same time. Participants performed two blocks of dual-task trials, with each block consisting of three cues for grasp–place–return tasks during five ramps of foot-pedal tracking (15 reaches during five ramps). Similar to the single-task conditions, sequences of steep and gradual target tracking ramps were randomly selected and counterbalanced across the 30 trials of three-phase reaches and 10 foot-pedal tracking ramps.

Data analysis

Hand position data were sampled at 120 Hz and filtered using a low-pass Butterworth filter with a 6-Hz cut-off frequency, and three-dimensional velocity profiles were derived (Marteniuk et al. 1987). Movement onset and offset of the upper limb reach task were defined as the time points when the hand velocity crossed above and below, respectively, 7 % of the peak velocity. Similarly, grasp, place, and return phase movement times were each defined as the durations delineated by respective thresholds of 7 % for each phase peak velocity and normalized to phase distance. The time spent in acceleration and deceleration for each phase of the reach was delineated by the time to peak velocity. Onset latency was defined as the time from the auditory cue to movement onset, and movement time was defined from movement onset to offset. Peak velocity, onset latency, movement time, and durations of acceleration and deceleration served as the outcome measures for the upper limb task performance. Although constant inter-cue intervals allowed participants to predict the start of the upper limb task, this predictability was similar in both the single- and dual-task conditions. Thus, the *relative change* in latency of reach onset from single- to dual-task conditions indicated how participants prioritized the two tasks when performed concurrently and the influence of dual-task interference. To examine issues of prioritization and the impact of dual-task interference on the three sequential phases of the reach task, we evaluated each phase (grasp, place, and return) for peak velocity and phase movement time in relation to the auditory cue to reach, and the durations of acceleration and deceleration within each phase. A subset of participants performed an additional block of single-task reach trials with instructed visual focus on the computer screen to control for potentially different visual information between the single- and dual-task reaching trials. Gaze was videotaped for all participants during all trials.

Pedal position data were sampled at 1000 Hz and filtered off-line using a Chebyshev type 2 second-order low-pass filter with 100 Hz corner frequency. Performance of the lower limb task was measured as the root-mean-square of the tracking error (RMSE). The RMSE was calculated for each ramp as: $\sqrt{\sum (P1_i - P2_i)^2 / n}$; the square root of the sum of the mean deviations of the actual pedal position (P1) from the target trace position (P2) at each sampled point (i), squared and divided by the duration of the tracking period (number of bins, n) to give the total RMSE value for the duration of the ramp. Prior to statistical analysis, the RMSE values were normalized to trial duration of the gradual ramp and steep ramp conditions. To evaluate the tracking error relative to the phase of the target ramp (incline, level, decline) and directly compare single- to dual-task tracking, we calculated segmental RMSE values beginning with the onset of the ramp incline. Thus, for both steep and gradual ramps, the phase 1-normalized RMSE included the incline, phase 2 included the level part, and phase 3 included the ramp decline (Fig. 1). These ramp phases were the same for single- and dual-task conditions. Additionally, to evaluate whether the reach movement affected the foot-pedal tracking task only during the reach or also between reaches, tracking accuracy data during the reach intervals, starting from the time from movement onset to offset, was compared with that during no-reach intervals beginning from the time of hand movement offset to the next movement onset.

In addition to the absolute measures of change in the upper and lower limb tasks, for each task outcome measure (upper limb: onset latency, movement time, peak velocity; lower limb: RMSE) we calculated a relative measure of change in performance between the single and dual tasks relative to the single task, the dual-task effect (DTE). We used the DTE to represent the effects of dual-tasking on upper and lower limb performance in positive (dual-task benefit) and negative (dual-task cost) directions. They were calculated as percent change: DTE $= \pm 100 \times$ (performance in dual task $-$ performance in single task) $\div$ performance in single task (Kelly et al. 2010). A positive multiplier was used when an increased value indicated performance improvement, as with velocity, while a negative multiplier was used when a decreased value represented performance improvement, as with error.

Statistical analysis

To assess the effects of single- and dual-task conditions and different inter-cue intervals on upper limb performance, a two condition (single and dual) by two inter-cue interval (slow ICI and fast ICI) repeated-measures analysis of variance (ANOVA) was performed on reach onset latency, overall reach movement time, peak velocity, and acceleration and deceleration durations. No significant main effects or interactions of inter-cue interval were found ($p > 0.05$ for all comparisons). Therefore, for the remainder of the analyses described below, the inter-cue interval was not treated as an independent variable. To control for visual information, comparisons of onset latency, movement time, and peak velocity between reach trials with and without instructed visual focus were performed and revealed no difference ($p < 0.05$). Therefore, the remaining analyses were performed using the data from the non-instructed reach trials.

Reach phase movement time, peak velocity, and acceleration and deceleration durations were assessed for effects of the phases of the reach task by a three phase (grasp–place–return) by two condition ANOVA with repeated-measures on all factors. The tracking error *during* reach intervals was compared with the tracking error *between* reach intervals with a two shape (steep, gradual) by two reach interval (during, between) repeated-measures ANOVA. The DTE was assessed in the upper and lower limb tasks for the impact of the phase of the reach task and of the phase and shape of the ramp task by two-way repeated-measures ANOVAs using the reach phase and the ramp phase and shape factors, respectively.

Lastly, to evaluate the trade-off between tasks with different measurement parameters and explore how the performance of one task varies with the performance of the other task in response to task difficulty, DTEs were plotted using a performance (or attention) operating characteristic (POC) paradigm (Dressel 2008; Kelly et al. 2010; Norman and Bobrow 1975). Inherent in dual-task analyses are the comparisons of two tasks, usually with different measurement parameters, e.g., gait and cognitive tasks; therefore, the proportional metric of DTE was used (Boisgontier et al. 2013; Kelly et al. 2013). The POC considers task prioritization by the shape of the plotted performance measures of one task relative to the other, identifying the POC curve as a function between theories of limited central capacities (Kahneman 1973) and multiple resource pools (Wickens 2002) of information processing. At one extreme, if performance declined in both tasks equally, data would fall along a line with unitary slope on the POC curve, implying purely resource-limited processes of attention. At the other extreme, if no task trade-off was necessary due to perfect resource sharing, data would fall along lines indicating perfect task performance, implying multiple resource pools for attention. Thus, a composite DTE value for the reach task, calculated as the sum of the phase-averaged peak velocity DTE and percentage of total movement time DTE, was compared with the RMSE-DTE of the steep and gradual ramp tracking tasks and was analyzed using paired samples *t* tests. Greenhouse–Geisser corrections for violations of sphericity and Bonferroni corrections for multiple comparisons were applied when needed. Newman–Keuls post hoc tests were performed where appropriate. Values were reported as means with standard error of the means (SEM), effect sizes were reported as partial eta-squared (η_p^2), and statistical significance was set at $p \leq 0.05$.

Results

Figure 1 depicts the experimental setup and example traces of the hand velocity, foot-pedal target, and pedal position of a single participant. This participant showed delayed reach onset, longer movement times, and overall lower peak velocities in the dual-task compared with the single-task reaches. Similarly, for the pedal tracking task, increased dual-task error was seen when compared with the single-task condition, regardless of ramp shape. Of particular note in the gradual ramp dual-task condition was the decreased velocity and longer movement time of the return phase of the first reach that coincided in time with the large increase in tracking error during the incline phase of the ramp. Such behavior suggested that this individual had difficulty attending to both the reaching and the pedal tracking tasks at the same time and was representative of behavior shown across all participants, as described below.

Performance during single- and dual-task conditions

Upper limb task

Onset latency Auditory cues were given to all participants, but due to technical issues cues were captured with only nine participants for the calculation of onset latency of reach. Despite the predictability of the cues in both conditions, participants initiated reaching significantly later under dual-task conditions (single: 154 ± 13 ms and dual: 321 ± 34 ms; $F_{(1,8)} = 27.06$, $p = 0.001$, $\eta_p^2 = 0.77$).

Movement time The reaching task took participants longer to complete during the dual-task compared with the single-task condition (single: 1545 ± 66 ms and dual: 1667 ± 65 ms; $F_{(1,11)} = 7.52$, $p = 0.019$, $\eta_p^2 = 0.41$). An interaction of condition and phase revealed that participants spent longer in the return phase of the reach task for the dual-task condition compared with the single-task condition

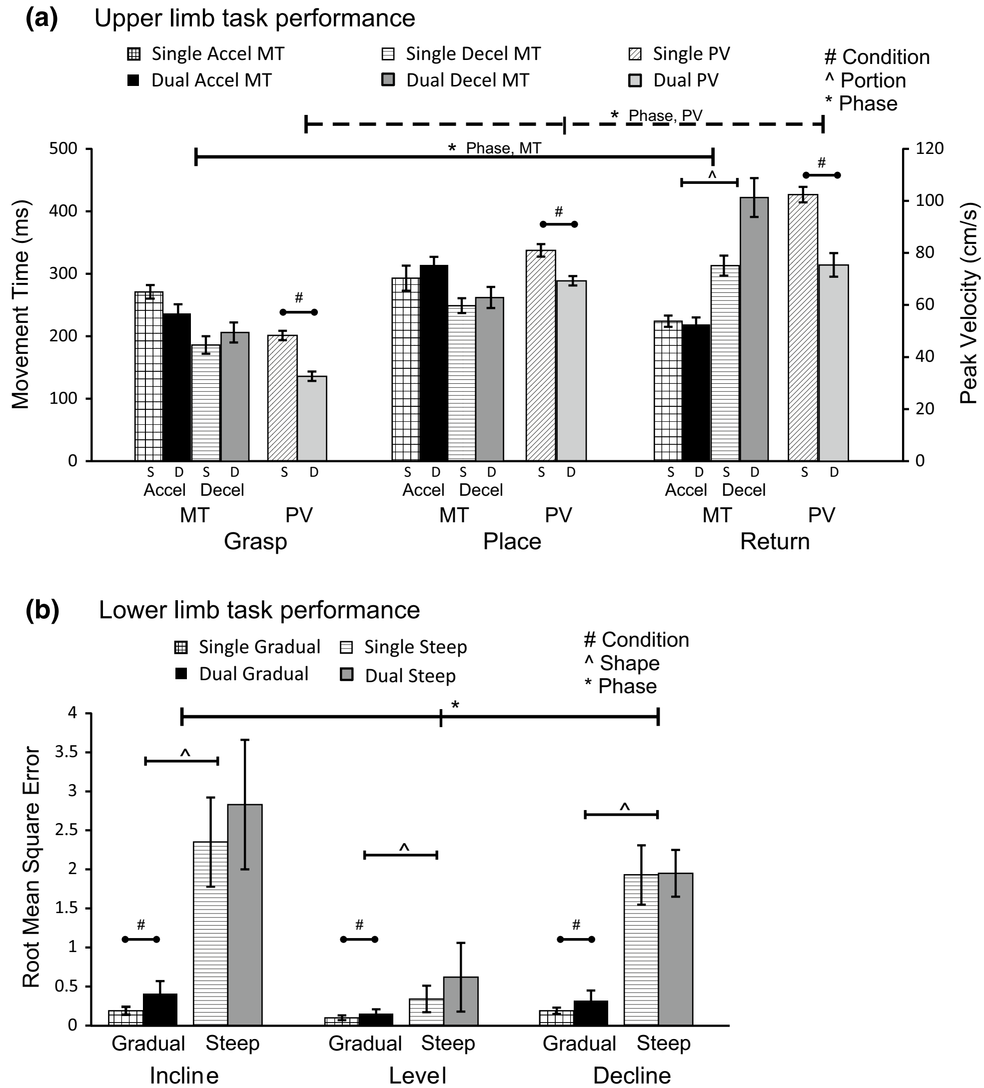

Fig. 2 Task performance for the **a** upper limb reach and **b** lower limb pedal tracking, by phase of each task (**a** grasp, place, return) and **b** incline, level, decline for single- (S) and dual-task (D) conditions. Phasic movement time (MT, *left axis panel* **a**) is shown as time spent in acceleration (accel) and deceleration (decel) portions of each phase of the reaching task. Peak velocity (PV, *right axis panel* **a**) of the hand during reach phases is shown. Segmental tracking error is shown as the phasic root-mean-square error (RMSE, *panel* **b**) for each phase of the foot-pedal tracking task. Values reported as means, standard error (SEM), and partial eta-squared (η_p^2) representing estimates of effect size. *Hash* represents main effect of condition, *hat* represents main effect of portion (accel, decel) in (**a**) and main effect of shape (steep, gradual) in (**b**), and *asterisk* represents main effect of phase

($F_{(2,22)} = 7.88$, $p = 0.003$, $\eta_p^2 = 0.41$), but the grasp and place phases were not affected by dual-tasking ($p < 0.05$; Fig. 2a left axis). The time spent in acceleration and deceleration portions of the reach was also related to single- and dual-task conditions; acceleration took longer than deceleration when single-tasking but was shorter than deceleration when dual-tasking (interaction of condition and portion: $F_{(1,11)} = 35.06$, $p < 0.001$, $\eta_p^2 = 0.76$; Fig. 2a left axis). Furthermore, post hoc analysis of a three-way interaction with condition confirmed that participants used a different strategy for acceleration and deceleration portions among phases according to conditions of dual- or single-tasking ($F_{(2,22)} = 8.00$, $p = 0.002$, $\eta_p^2 = 0.42$; Fig. 2a left axis). Notably, participants responded to the dual-task condition by reducing the duration of acceleration and increasing the duration of deceleration in the grasp and return phases ($p < 0.05$ all comparisons; Fig. 2a left axis) with no condition-related change during the place phase of the reach task ($p < 0.05$).

Peak velocity Participants achieved higher peak velocities during the reaching task under single-task rather than dual-task conditions (single: 77.2 ± 1.7 cm/s; dual: 59.1 ± 2.0 cm/s; main effect of condition: $F_{(1,11)} = 70.84$, $p < 0.001$, $\eta_p^2 = 0.87$; Fig. 2a right axis). Progressively greater peak velocities were achieved in sequential reach phases (main effect of phase: $F_{(2,22)} = 113.07$, $p < 0.001$, $\eta_p^2 = 0.91$; Fig. 2a right axis). A condition by phase interaction ($F_{(2,22)} = 7.54$, $p = 0.003$, $\eta_p^2 = 0.41$) and post hoc analyses indicated that the condition-related velocities were similar during the grasp and place phases ($p > 0.05$), whereas in the return phase higher velocities occurred in the single-task compared with the dual-task condition ($p < 0.05$) (Fig. 2a right axis).

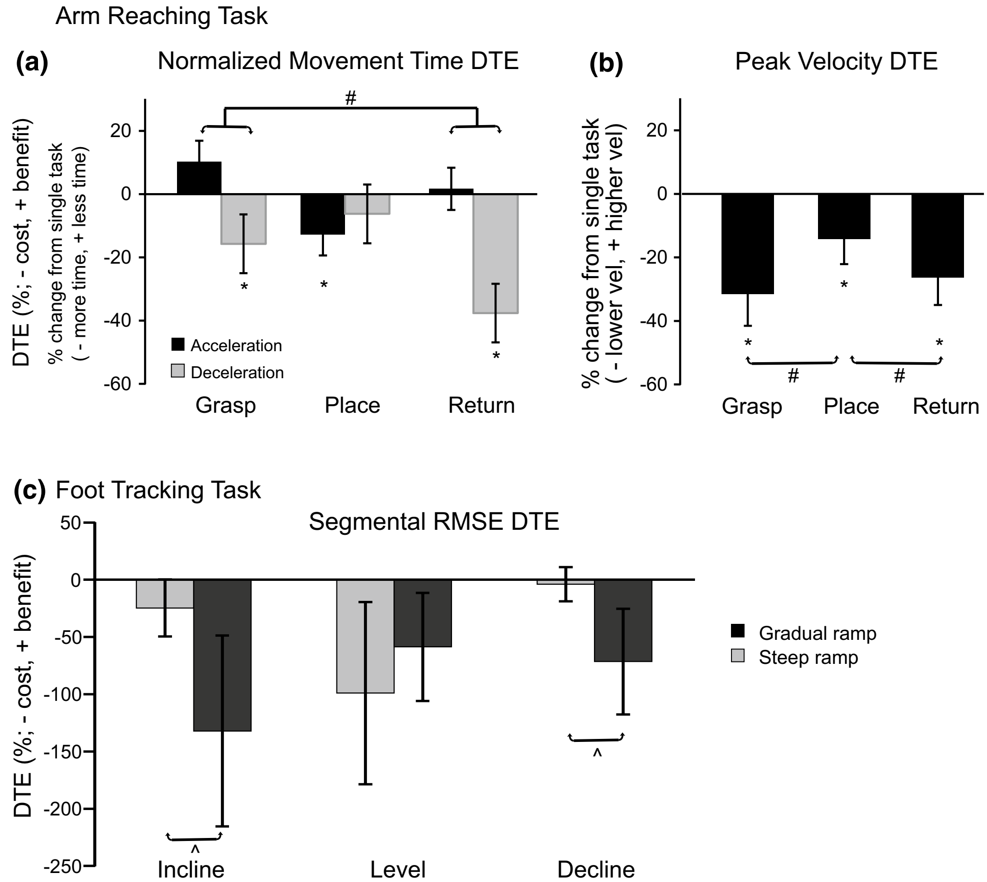

Fig. 3 Dual-task effects (DTEs) on performance of the reaching and foot-pedal tracking tasks. Shown are the mean DTEs on the **a** relative time in acceleration (*dark*) and deceleration (*light*) and **b** peak hand velocity of the grasp, place, and return phases of the reaching task, and to the **c** segmental root-mean-square error (RMSE) of the incline, level, and decline phases of the foot-pedal tracking task during the steep (*light*) and gradual (*dark*) ramp conditions. *Error bars* represent standard error of the means, *asterisk* represents a significant difference from zero, *hash* represents a phase difference, and *hat* represents a difference between ramp shapes ($p \leq 0.05$ for all)

Lower limb task

Tracking error

Performing foot-pedal tracking simultaneously with the reaching task resulted in greater tracking error compared with the single-task (single: 0.84 ± 0.04; dual: 1.03 ± 0.06; $F_{(1,11)} = 11.13$, $p = 0.007$, $\eta_p^2 = 0.50$; Fig. 2b). There was a main effect of ramp shape on tracking performance, such that participants demonstrated greater error during the steep ramps compared with the gradual ramps (gradual: 0.23 ± 0.02; steep: 1.67 ± 0.08; $F_{(1,11)} = 345.17$, $p < 0.001$, $\eta_p^2 = 0.97$; Fig. 2b). Closer examination of tracking during phases of the ramp task revealed a main effect of phase ($F_{(1,11)} = 130.44$, $p < 0.001$, $\eta_p^2 = 0.97$) where participants had the greatest segmental tracking errors during the incline phase (1.44 ± 0.09), significantly fewer errors during the decline phase (1.10 ± 0.05), and the least errors during the level phase (0.30 ± 0.04) (all pairwise comparisons $p < 0.003$, Fig. 2b). However, no interactions with condition were found to influence tracking performance ($p > 0.05$). During dual-task trials, tracking errors sustained *during* the reach were greater than errors sustained *between* reaches (during: 1.38 ± 0.09; between: 0.73 ± 0.07), ($F_{(1,11)} = 144.8$, $p < 0.001$, $\eta_p^2 = 0.93$).

Dual-task effects: the cost to performance

Upper limb

Participants experienced different amounts of relative change in performance across phases of the reach task as a result of dual-tasking with the foot, as measured by DTE. While dual-tasking did not exact a cost to the normalized movement time of the grasp and place phases (grasp, 2.7 ± 04.6 %; place, −7.0 ± 3.2 %; $p > 0.05$), it did result in a cost to the return phase of the reach task (−20.0 ± 5.6 %) (main effect of phase: $F_{(2,22)} = 7.76$, $p = 0.003$, $\eta_p^2 = 0.41$; $p < 0.05$ for both comparisons). Closer examination of the dual-task effects on the acceleration and deceleration portions of each phase revealed a significant interaction of portion and phase ($F_{(2,22)} = 6.95$, $p = 0.005$, $\eta_p^2 = 0.39$) (Fig. 3a). Post hoc analysis revealed that dual-tasking caused increased time in acceleration (a DTE cost) in the place phase ($t_{(11)} = -2.58$, $p = 0.026$) and no difference from zero for the DTE on acceleration in the grasp and return phases ($p > 0.05$ both t tests). In contrast, dual-tasking caused increased deceleration time (greater costs) in the grasp and return phases ($p < 0.05$ both t tests) and no dual-task effects during the place phase ($p > 0.05$)

(Fig. 3a). Corresponding with the dual-task increase in total movement time, peak velocity sustained the greatest cost (declined) during the grasp and return phases ($F_{(2,22)} = 5.80$, $p = 0.009$, $\eta^2_p = 0.35$; $p < 0.05$ for both comparisons; Fig. 3b) and all were significantly different from zero ($p < 0.05$ all t tests),

Lower limb

Participants experienced greater cost to foot-pedal tracking in the gradual ramp compared with the steep ramp (gradual ramp, −87.4 ± 23.5 %; steep ramp, −42.5 ± 12.9 %; $F_{(1,11)} = 6.95$, $p = 0.02$, $\eta^2_p = 0.39$). This effect of ramp shape was primarily influenced by the significant interaction with phase ($F_{(2,22)} = 7.91$, $p = 0.003$, $\eta^2_p = 0.42$) where the incline and decline portions sustained less cost to tracking during the steep ramps compared with the gradual ramps ($p < 0.05$), but the costs were equivalent between ramp shapes during the level phase ($p > 0.05$) (Fig. 3c).

Between-task trade-off

The effects of ramp shape with corresponding cue intervals on trade-offs between the reaching and foot-pedal tracking tasks was examined within a POC framework. The composite DTE of the arm task was plotted against the DTE of the foot-pedal tracking task (Fig. 4). Paired samples t tests of the arm and foot task DTEs confirmed that when participants performed the reaching and pedal tracking tasks together during the gradual ramp, the overall dual-task cost to the foot task was greater than to the arm task ($t_{(11)} = 2.33$, $p = 0.04$), but was similar when performed during the steep ramp ($t_{(11)} = -0.91$, $p = 0.38$). These findings are represented in Fig. 4 as the "gradual ramp" marker positioned further left on the abscissa than the "steep ramp" marker, which is further from the dashed vertical line and of equal distance from the dashed horizontal line representing single-task performance. Thus, the overall arm task was prioritized over the foot task during the gradual ramp condition, but the limb tasks were given equal priority in the steep ramp condition.

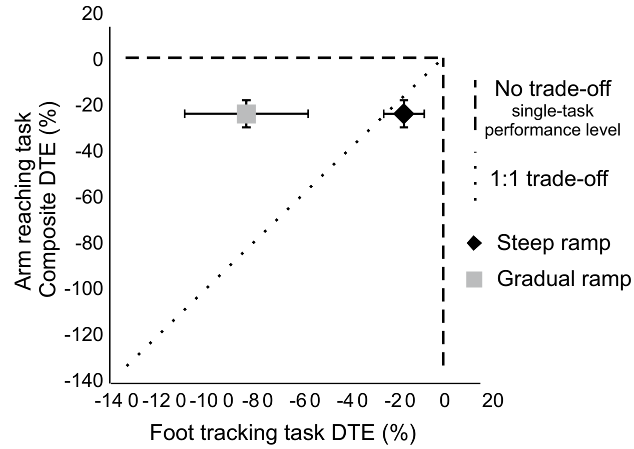

Fig. 4 Between-task trade-off. The performance operating characteristic (POC) plot depicts the effects of ramp shape on the mean (±standard error of the mean) dual-task effect (DTE) of the foot-pedal tracking task and composite DTE of the arm reaching task relative to each other. The *diagonal dotted line* represents the potential situation of equal 1:1 task trade-off, implying purely resource-limited processes of attention. The *dashed vertical* and *horizontal lines* represent the other extreme of no task trade-off because of perfect resource sharing, implying multiple resource pools for attention

Discussion

The present study is the first to characterize dual-task interference effects and attention allocation among upper and lower limbs in a novel multi-limb seated task which mimics driving-like behaviors. When performing the three-phase arm reaching task and the foot-pedal, ramp-tracking task simultaneously, participants reached later, took more time to reach, and moved more slowly than when reaching alone. Likewise, the accuracy of their foot-pedal tracking declined when they were simultaneously reaching more than when they were only tracking. This effect was more pronounced during the gradual ramp than the steep ramp conditions. In terms of the relative cost to performance from dual-task interference, the three phases of each task sustained different degrees of performance cost. First, the grasp and return phases of reaching sustained a cost in the time spent in deceleration and in hand velocity. Second, the accuracy of the foot-pedal tracking sustained a greater dual-task cost in the gradual ramp condition specifically in phases that were related to ramp shape. Finally, participants showed a trade-off between arm and foot tasks; the arm task was prioritized over the foot task during the gradual ramp, whereas the tasks were given equal priority during the steep ramp. In the following paragraphs, we will discuss these results in the context of task structure, dual-task attention, and strategies for allocation and prioritization.

These findings suggest that healthy young adults have processing and attention limitations for simultaneously reaching and controlling a foot pedal and thus prioritized or allocated attention to the tasks accordingly. In light of increasing use of hand-held devices and crashes related to their use while driving (National Highway Traffic Safety Administration 2014), these findings provide a basis on which to explore, identify, and potentially train multi-limb attention allocation strategies for driving in healthy and in vulnerable populations.

Implications of the task structure on dual-task interference

Overall, our findings reflect the structure of the multi-limb dual-task designed for this study, revealing that performance cost varies with the phase of the limb task and that limb task prioritization strategies vary with the shape of the tracking ramp. Our dual task was designed to be ecologically valid, and mimicked behaviors frequently carried out while driving (Stutts et al. 2005). Participants performed a three-phase reaching task that mimicked grasping and moving an object, such as a music CD, and a foot-pedal tracking task following targets that mimicked rapid and slow acceleration and deceleration, e.g., following another car and brief periods of speed maintenance. Instructions for prioritization of any phase of the reach task were purposely withheld to observe which strategies were self-selected according to task structure. This was important for first characterizing multi-limb control related to the structure of the task alone, without adding the influence of modulating task priority.

Studies on the control of reaching to grasp indicate the hand follows a characteristic path, accelerating to reach its peak velocity between 40 and 50 % of the movement duration then decelerating until the object is grasped, with some variation depending on properties and location of the object (Supuk et al. 2011; van Vliet et al. 2013). The acceleration portion of the reach is thought to be planned and executed prior to movement onset in a feed-forward manner (Nagasaki 1989). In contrast, the deceleration portion of the reach is considered to be controlled through feedback in which sensory information is used for "online" movement adjustments according to task goals and context (van Vliet et al. 2013). Thus, the reduced time in acceleration and increased time in deceleration seen with dual-tasking in the grasp, and return phases of our reach task implied participants spent less time in feed-forward control and more time in feedback control. Such a strategy takes more time but recruits sensory inputs to maintain reach performance when under heightened attentional load from dual-tasking. Without explicit accuracy constraints, participants may have prioritized the grasp phase over the subsequent phases. This speculation is supported by our findings of overall lower peak velocity and relatively longer acceleration times for this phase. The serial nature of the phases may have influenced prioritization according to order in the sequence. Indeed, relative movement time and peak hand velocity increased with subsequent phases. However, when normalized to the individual's single-task performance, the small difference in grasp phase velocity from single to dual task became a relatively significant cost (~30 %). These findings suggested that the greatest dual-task processing interferences occurred during the initial grasp phase and when returning the hand to the start position.

Alternatively, the dual-task planning and processing of the upper limb task may have been done separately by phase instead of holistically. This alternative is based on our finding that the dual-task cost of grasp and place phase durations was similar, while the cost of the return phase duration was much greater. Such differences might indicate participants executed and processed phases of the upper limb task separately, specifically the grasp and place phases together and then the return phase. During the transition between place and return phases, participants may have allocated their attention away from the upper limb to maintain performance of the lower limb task and then shifted their attention back to complete the upper limb task. A similar phenomenon was reported in a driving and phone dialing dual-task study (Janssen et al. 2012). The authors of that study found that instead of completing number dialing at one time, individuals tended to interleave the dialing task, briefly shifting their attention toward the driving task and before shifting back to finish dialing. In similar manner in the present study, participants may have allocated their attention away from the upper limb to maintain performance of the lower limb task during the transition between the place and return phases before shifting their attention back to complete the upper limb task, which caused the increased movement time for the return phase. Supporting this speculation of attention shifts, we found that the tracking error of the foot task was considerably less during reaching than between reaches.

Performance on the foot task also reflected the structure of the tracking ramps. As expected, the segmental tracking error was least during the level phase of the ramp compared with the incline and decline portions. During most of the level phase, participants needed to maintain a constant pedal position, similar to the control needed to maintain a constant car speed when driving. Although the amount of error was greater in the steep than the gradual ramps, the relative change in error due to dual-tasking was greater in the gradual ramps than the steep ramps. Regardless of phase, gradual ramp tracking was overall twice as costly as steep ramp tracking, with these shape-related differences largely due to the dynamic phases (incline and decline). This result implied a greater requirement for attentional resources during dynamic rather than during level tracking, at least for the gradual ramp. Such findings were consistent with car-following driving behavior where variable car speed is caused by distraction from checking the speedometer or mirror (Brackstone and McDonald 2007). In addition, dynamic tracking may be less attentionally demanding at faster speeds than slower speeds although this speculation needs to be specifically explored. Thus, our findings of dual-task cost in performance of the arm reaching and foot-pedal tracking tasks supported our hypothesis that there would be a limitation for attention and information processing of both tasks in healthy young adults. Furthermore, the limitation of this cost to performance was modulated by the structure of each task.

Attention allocation and trade-off between arm and leg tasks

The experimental task of the present study was designed to test the dual-task interference on performance of the arm and leg tasks without the influence from control of upright standing or walking posture. The "posture first" strategy, first coined by Shumway-Cook et al. (1997), describes the principle by which attention is allocated to postural control (e.g., walking or standing) to prioritize stability over the secondary task that is being performed concurrently. However, prioritizing posture is not universal; rather, strategies for allocating attention seem to be flexible and related to the perceived value of the tasks, estimation of risk, and other factors of the environment, individual, and task (Kelly et al. 2013; Rapp et al. 2006; Shumway-Cook et al. 1997; Yogev-Seligmann et al. 2012). In the present study, we sought to determine whether this concept would extend to self-selected prioritization of a lower limb task that was not linked to upright postural control (e.g., participants were sitting). Participants experienced dual-task costs in both limb tasks with a between task trade-off related to the shape of the tracking ramp, which implied that attention allocation was flexibly shifted toward the arm task during the gradual ramp and equally allocated between tasks during the steep ramp. Modification of the timing or scheduling of the tasks may have allowed participants to optimize information processing and avoid a processing bottleneck.

Task prioritization may have been organized by participants modifying the timing or scheduling of the tasks to optimize information processing and avoid a processing bottleneck (Navon and Miller 2002; Pashler 1994; Schumacher et al. 2001; Van Mier et al. 1993). Inherent to this scheduling issue is the type of tasks, continuous or discrete, that are performed together. Participants in the present study may have *temporally* prioritized the discrete and relatively brief reaching task to complete it quickly before returning their attention to the ongoing and continuous tracking task. Specifically, participants had similar durations of reach phases and whole reach durations whether they were given 3 or 6 s between cues. Thus, even if given a longer duration, they did not utilize the extended time to expand their reach duration. Instead, they completed the task just as quickly, leaving more time for switching attention back to the foot-pedal task and optimizing dual-task attention. These findings are consistent with the findings of Meyer and Kieras (1997a, b). In their studies of adaptive executive control models for dual-task performance, procedural knowledge was used as condition-action production rules and some stages of one task were selectively postponed while another task was underway (Meyer and Kieras 1997a, b). In our study, the gradual ramp tracking task produced greater relative cost to the foot-pedal task than the steep ramp. Together, these results suggested that the ramp shape, but not the inter-cue interval for reach, impacted the task prioritization strategy.

Limitations and future studies

There are limitations to this study that must be considered. Although the effect sizes were moderate to large in most analyses, the sample size is small and thus results need to be replicated in larger samples for reliability. We used the proportional metric of the DTE specifically to compare different types of variables between limb tasks (RMSE, peak velocity, movement time); however, inherent nonlinearity of any variable could potentially introduce some inflation in the DTE values, differently across variables. The primary aim of within-task comparison of single- to dual-task performance would presumably have consistent nonlinearity and thus reliable comparisons to evaluate dual-task interference effects. Future studies could explore the effect of the nonlinearity of variables on DTE. While the phases of the foot-pedal tracking task were delineated by the incline, level, and decline parts of the ramps, the auditory cues to reach occurred at different places within the steep compared with the gradual ramp. For instance, the second cue for reaching occurred 1.3 s into the level phase of the steep ramp and 0.5 s before the end of the incline phase of the gradual ramp, and cue 3 occurred 0.6 s before the end of the level phase of the steep ramp and 0.5 s into the decline phase of gradual ramp. Therefore, it is possible during the dual-task conditions that complexity of the ramp phases differed somewhat between the steep and gradual ramps and may have contributed to greater dual-task costs to tracking error specifically in the incline phase of the gradual ramp and the level phase of the steep ramp. Current studies are underway to control for this possibility. However, the timing of the cues relative to ramp phases was consistent between the single- and dual-task conditions, the comparison used for calculations of the dual-task effect.

Conclusion

In the present study, we reported for the first time on the dual-task costs to performance and task prioritization of functionally based arm and leg tasks in the absence of cyclic ongoing movements and concerns of gait-related postural control. We propose that attention to concurrent reaching and foot-pedal tracking is flexibly allocated and tasks are prioritized based on the structure of the tasks.

From this baseline, characterization of dual-task interference among limbs, factors of instructed priority, perceived risk and value of the tasks, and of task type (discrete reaching versus continuous steering) can be explored.

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References

Bloem BR, Valkenburg VV, Slabbekoorn M, Willemsen MD (2001) The multiple tasks test: development and normal strategies. Gait Posture 14:191–202

Boisgontier MP, Beets IAM, Duysens J, Nieuwboer A, Krampe RT, Swinnen SP (2013) Age-related differences in attentional cost associated with postural dual tasks: increased recruitment of generic cognitive resources in older adults. Neurosci Biobehav Rev 37:1824–1837

Brackstone M, McDonald M (2007) Driver headway: how close is too close on a motorway? Ergonomics 50:1183–1195

Diermayr G, McIsaac TL, Kaminski TR, Gordon AM (2011) Aging effects on object transport during gait. Gait Posture 34:334–339

Dressel J (2008) Measuring dual task cost using the performance operating characteristic: the effect of emotional words on one's functional field of view Doctoral Dissertation 3315981. University of Kansas, Kansas

Federal Highway Administration (2012) Highway statistics 2012—distribution of licensed drivers. http://www.fhwa.dot.gov/policyinformation/statistics/2012/dl20.cfm. Accessed June 06 2014

Fitch GA et al (2013) The impact of hand-held and hands-free cell phone use on driving performance and safety-critical event risk. National Highway Traffic Safety Administration, Washington, DC

Gysin P, Kaminski TR, Hass CJ, Grobet CE, Gordon AM (2008) Effects of gait variations on grip force coordination during object transport. J Neurophysiol 100:2477–2485

Janssen CP, Brumby DP, Garnett R (2012) Natural break points: the influence of priorities and cognitive and motor cues on dual-task interleaving. J Cogn Eng Decis Making 6:5–29

Kahneman D (1973) Attention and effort. Prentice-Hall series in experimental psychology. Prentice-Hall, Englewood Cliffs, NJ

Kelly VE, Janke AA, Shumway-Cook A (2010) Effects of instructed focus and task difficulty on concurrent walking and cognitive task performance in healthy young adults. Exp Brain Res 207:65–73

Kelly VE, Eusterbrock AJ, Shumway-Cook A (2013) Factors influencing dynamic prioritization during dual-task walking in healthy young adults. Gait Posture 37:131–134

Laessoe U, Hoeck HC, Simonsen O, Voigt M (2008) Residual attentional capacity amongst young and elderly during dual and triple task walking. Hum Mov Sci 27:496–512

Lajoie Y, Teasdale N, Bard C, Fleury M (1993) Attentional demands for static and dynamic equilibrium. Exp Brain Res 97:139–144

Marteniuk RG, MacKenzie CL, Jeannerod M, Athenes S, Dugas C (1987) Constraints on human arm movement trajectories. Can J Psychol 41:365–378

Meyer DE, Kieras DE (1997a) A computational theory of executive cognitive processes and multiple-task performance: part 1. Basic mechanisms. Psychol Rev 104:3–65

Meyer DE, Kieras DE (1997b) A computational theory of executive cognitive processes and multiple-task performance: part 2. Accounts of psychological refractory-period phenomena. Psychol Rev 104:749–791

Nagasaki H (1989) Asymmetric velocity and acceleration profiles of human arm movements. Exp Brain Res 74:319–326

National Highway Traffic Safety Administration (2014) Distracted driving facts and statistics. US Department of Transportation. http://www.distraction.gov/content/get-the-facts/facts-and-statistics.html. Accessed 23 December 2014

Navon D, Miller J (2002) Queuing or sharing? A critical evaluation of the single-bottleneck notion. Cogn Psychol 44:193–251

Norman DA, Bobrow DG (1975) On data-limited and resource-limited processes. Cogn Psychol 7:44–64

Pashler H (1994) Dual-task interference in simple tasks: data and theory. Psychol Bull 116:220–244

Plummer-D'Amato P, Cohen Z, Daee NA, Lawson SE, Lizotte MR, Padilla A (2012) Effects of once weekly dual-task training in older adults: a pilot randomized controlled trial. Geriatr Gerontol Int 12:622–629

Rapp MA, Krampe RT, Baltes PB (2006) Regular research article: adaptive task prioritization in aging: selective resource allocation to postural control is preserved in Alzheimer disease. Am J Geriatr Psychiatry 14:52–61

Schumacher EH, Seymour TL, Glass JM, Fencsik DE, Lauber EJ, Kieras DE, Meyer DE (2001) Virtually perfect time sharing in dual-task performance: uncorking the central cognitive bottleneck. Psychol Sci 12:101–108

Shumway-Cook A, Woollacott M, Kerns KA, Baldwin M (1997) The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. J Gerontol Ser A-Biol Sci Med Sci 52A:M232–M240

Stutts J, Feaganes J, Reinfurt D, Rodgman E, Hamlett C, Gish K, Staplin L (2005) Driver's exposure to distractions in their natural driving environment. Accid Anal Prev 37:1093–1101

Supuk T, Bajd T, Kurillo G (2011) Assessment of reach-to-grasp trajectories toward stationary objects. Clin Biomech 26:811–818

Van Mier H, Hulstijn W, Petersen SE (1993) Changes in motor planning during the acquisition of movement patterns in a continuous task. Acta Psychol 82:291–312

van Vliet P, Pelton TA, Hollands KL, Carey L, Wing AM (2013) Neuroscience findings on coordination of reaching to grasp an object: implications for research. Neurorehabil Neural Repair 27:622–635

Wickens CD (2002) Multiple resources and performance prediction. Theor Issues Ergon Sci 3:159–177

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 JM, Giladi N (2008) The role of executive function and attention in gait. Mov Disord 23:329–342

Yogev-Seligmann G, Hausdorff JM, Giladi N (2012) Do we always prioritize balance when walking? Towards an integrated model of task prioritization. Mov Disord 27:765–770