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Working Memory and Postural Control: Adult Age Differences in Potential for Improvement, Task Priority, and Dual Tasking

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Working Memory and Postural Control: Adult-Age Differences in Potential for
Improvement, Task-Priority and Dual-Tasking

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Abstract

We investigate dynamic posture control and working memory (NBack) retest practice in young and older adults, focusing on older adults' potential for improvement in the component tasks, but more importantly in dual-task performance. Participants performed the two tasks in 11 sessions under single- and dual-task conditions. Posture improvement was observed with retest practice for both groups. Increase in cognitive load after initial practice led to greater dual-task costs (DTCs) in both tasks in older and higher costs in memory in young adults. With continued practice, costs were reduced by both groups, however the two groups focused improvement on different tasks: Older adults focused on posture but young on cognition. These results emphasize older adults' potential for improvement in dual-task performance, and their flexibility to utilize the practice gains in posture to optimize cognitive performance.

Keywords: dual-task, aging, posture, balance, working memory, resource allocation, risk of falling

Working Memory and Postural Control: Adult-Age Differences in Potential for Improvement, Task-Priority and Dual-Tasking

Standing balance is a seemingly effortless task for young adults, easily performed at the same time with other tasks such as talking, or remembering a shopping list. However, multitasking in everyday settings may be more difficult for older adults, due to age-related decline in cognitive and sensorimotor processing. For example, imagine a young and an older adult standing on a bus and talking. If the bus goes over a speed bump introducing additional challenges to postural control, it is more likely for the older adult to interrupt the conversation and focus his resources on posture, thereby avoiding a potential fall. Recent evidence suggests that in **older adults** postural control requires attentional resources (Woollacott & Shumway-Cook, 2002). When two tasks (i.e. posture-memory) are performed at the same time (dual-task), and they require more than the total amount of available resources, dual-task costs (DTCs) are observed, i.e. performance on either or both tasks declines. These limits will be reached faster (i.e., costs will be higher) in older adults, given that their overall resources are reduced relative to young adults' and that sensorimotor control declines with age (Lindenberger, Marsiske, & Baltes, 2000; Woollacott & Shumway-Cook, 2002).

Understanding the way resources are allocated is an especially critical issue for current aging research, as shown by recent studies assessing sensorimotor-cognitive dual-task performance including sensorimotor tasks such as posture (Domas, Smolders, & Krampe, 2008), walking (Lovden, Schaefer, Pohlmeier, & Lindenberger, 2008), force control (Voelcker-Rehage & Alberts, 2007) and coordination of hand-foot movements (Heuninckx, Debaere, Wenderoth, Verschueren, & Swinnen, 2004). Posture is of particular interest for aging research because lack of control in this task increases the possibility of a fall, the

leading cause of accidental death among older adults (Fuller, 2000). Recent studies comprising posture-cognition dual-task performance suggest that when instability increases older adults allocate more attentional resources to posture control than to cognition in order to avoid fall accidents. This pattern of resource allocation was demonstrated in recent studies, by introducing a manipulation of task difficulty (instability) in posture, including the low difficulty (stable) condition of quiet standing and the high difficulty (unstable) condition of standing on a moving surface (Brown, Sleik, Polych, & Gage, 2002; Doumas, Smolders, & Krampe, 2008; Rapp, Krampe, & Baltes, 2006). These studies showed that older adults directed their resources from cognition to posture only when instability increased, thereby prioritizing postural stability over cognitive performance.

Li and colleagues (2001) demonstrated similar adaptivity in older adults' resource allocation. In their study young and older adults memorized word lists while walking a track with obstacles. Older adults showed higher DTCs in memory than young adults, whereas decrements in walking were comparable for the two age groups. When participants were provided with external aids assisting their performance the two age groups prioritized different tasks; older adults utilized the walking aid (a handrail) to optimize sensorimotor performance, whereas young adults made more frequent usage of memory aids choosing to optimize cognition. Evidence from dual-task studies and research focusing on the occurrence of falls (Berg, Alessio, Mills, & Tong, 1997; Connell & Wolf, 1997) suggests that age-related problems in dual-tasking might contribute to falls in older adults. Improving concurrent cognitive and balance performance may thus be essential, not only in rehabilitation, but as a means of fall prevention that fosters functional independence and improves the quality of life in healthy older adults.

Age-Differential Improvement in Cognitive and Sensorimotor Tasks

There is wide agreement in the literature that older adults can improve performance in cognitive tasks through systematic cognitive training or in the course of extensive retesting, but evidence is mixed with respect to adult-age differences in rate and potential for improvement. While some studies found similar improvement on new tasks or skills in young and older adults (Hertzog, Williams, & Walsh, 1976; Peretti, Danion, Gierski, & Grange, 2002; Salthouse, 1990; Scialfa, Jenkins, Hamaluk, & Skaloud, 2000), others observed a magnification of initial age differences after extensive laboratory training in a mnemonic skill (Kliegl, Smith, & Baltes, 1990). Such limitations in plasticity (trainability) for acquiring new, complex cognitive skills appear to be pronounced in very old age (Singer, Lindenberger, & Baltes, 2003). Using a retest paradigm, Yang et al. (2006) demonstrated reductions from the seventh to the eighth decade of life in plasticity for improving on basic cognitive functions (reasoning and mental speed) but even the oldest participants had preserved some plasticity.

Regarding improvement in sensorimotor tasks, posture and gait training have been successfully used in rehabilitation to assist balance recovery in clinical populations, such as hemiparetic stroke patients and fall prone individuals. Recent balance training studies in older adults used tasks such as wobble board or mini trampoline training and showed improvements in proprioception (joint position sense) in the ankle (Waddington & Adams, 2004) and the knee (Diracoglu, Aydin, Baskent, & Celik, 2005). Balance intervention studies have also used Tai-Chi as a way of improving balance in older adults, however, these studies assessed primarily the occurrence of falls (F. Z. Li, Fisher, Harmer, & McAuley, 2005; F. Z. Li et al., 2005) rather than posture control per se. A recent study suggests that the beneficial effects of Tai-Chi are not evident using measurements of posture control (Woo, Hong, Lau,

& Lynn, 2007). Thus, it is still unclear whether and to what degree older adults' posture control improves with training.

Fewer studies have examined improvement in dual-tasking with training and those who did used combinations of two cognitive tasks. Kramer and colleagues (Kramer, Larish, & Strayer, 1995; Kramer, Larish, Weber, & Bardell, 1999) showed that given proper training, older adults can improve their dual-task performance and also learn to flexibly allocate resources to either component task. The only study of older adults' dual-task improvement in posture-cognition settings (Silsupadol, Siu, Shumway-Cook, & Woollacott, 2006) compared single- and dual-task training in three balance impaired older adults. However, systematic evidence related to healthy older adults' potential for improving in posture-cognition dual-tasking and related differences compared with young adults is missing from the literature.

Outline of the Study

In the present study we investigated healthy young and older adults' improvement through retest practice in concurrent posture and working memory performance. We asked were whether young and older adults could improve in dual-tasking over and above improvements in single-task performance and whether improvement was similar for cognitive and posture tasks in both age groups. To this end we used a retest paradigm over the course of 11 sessions, during which participants were tested on the NBack working memory task (Dobbs & Rule, 1989), on postural stability while standing upright on a tilting platform, and on concurrent performance of the two tasks.

Studying age related differences in dual-task improvement presumes a demonstration of DTCs and experimental control over the amount of these costs. However, age differences in DTCs can be the result of ceiling (typically in young adults) or floor (typically in older

adults) levels of single-task performance. We approached these problems by individually adjusting accuracy in the cognitive task and by organizing our study in two phases: In the first five sessions (first phase), participants performed the cognitive task at a low level of difficulty (NBack-2), concurrently with the posture task. After session five (second phase), we increased the overall level of cognitive load by going from NBack-2 to NBack-3 and by individually adjusting presentation rates in order to achieve 80% or 100% performance accuracy under single-task conditions. That way, we aimed to establish a common single-task baseline for all participants, making retest assessment of dual-task decrements comparable between age groups, and avoiding floor and ceiling effects. During the second phase of the study participants' single- and dual-task performances and their improvement were assessed using retest practice.

We expected overall improvement of single-task postural control in young and older adults throughout the study. With respect to DTCs, we predicted that the increase in cognitive load early in the second phase would lead to higher costs in older than in young adults. We also expected that in the second phase, the individual adjustment of cognitive load would occupy all the available resources in single-task cognition, thus, the additional resources required for posture-cognition dual-tasking would cause an increase in DTCs in posture, especially in older adults. Subsequently, however, we expected young as well as older adults to reduce these elevated DTCs during extensive retesting. Finally, following evidence by Li et al. (2001) for differential task priority in walking and memory, we predicted that during dual-task retesting older adults would mostly improve their postural control, while young adults would optimize cognitive performance.

Method

Participants

Eight young (four female, four male; aged 25-29 years, mean 26.55 years, SD 1.87 years) and 10 older adult volunteers (6 female, 4 male; aged 62 - 71 years, mean 66.86 years, SD 3.26 years) participated in the present study. The study included only participants scoring at least 28 in the Mini Mental State Examination to rule out effects of dementia. They were recruited from the subject database of the Max Planck Institute (MPI) for Human Development in Berlin, and were paid 10 Euros per session for their participation. The study was approved by the institute's ethics committee.

Apparatus

In single-task performance, for the cognitive task participants sat at a table and stimuli were presented using a monitor connected to a Power Macintosh 7100/80 Computer. In dual-task performance, a Pentium III PC was used for stimulus presentation. For posture measurements participants stood on a 40 x 60 cm Kistler 9286A multicomponent force platform (Kistler Instrumenten AG, Winterthur, Switzerland). Piezoelectric sensors located at the corners of the platform provided a 12-channel recording of lateral, vertical, and anterior-posterior forces and their momentums. The platform was mounted on a robotic axis (Power Cube Rotari PR 110, mcm Prüfsysteme GmbH, Berlin, Germany). Movement amplitude and angular velocity were controlled by a μ -musics computer (μ -M-S Eth-RJ45; mcm Prüfsysteme GmbH) which also sampled the 12-channel recordings at a rate of 10 kHz.

Tasks and Procedure

In single-task conditions participants performed either the cognitive or the posture task. For the cognitive task, they were asked to name single digits (one to nine) presented successively at a Stimulus Onset Asynchrony (SOA) which varied between 2500 and 1000 ms depending on session and individually adjusted difficulty level (see below). Stimuli were presented on a computer screen at a random order (Stimulus duration: 500 ms). Working memory was challenged by asking participants to name the stimulus presented two (NBack-2, sessions 1, 2, 4 and 5) or three cycles (NBack-3, sessions 6-11) before the current stimulus. Participants started from the third (NBack-2) or fourth (NBack-3) digit in each trial. Working memory performance was assessed by two experimenters, writing down the items verbalized at a given trial. The number of correct items named from the beginning of the trial until the first error was recorded as the number of correct items¹.

Postural control was assessed under stable and moving (sinusoidal platform rotations in the sagittal plane about the ankle joint axis, Frequency: 0.3 Hz, Amplitude: 3°) platform conditions or while participants stabilized after surprise perturbations (platform tilts). The focus of this paper is on the moving platform condition. In dual-task conditions participants performed the cognitive task (NBack-2 or NBack-3) as accurately as possible, while maintaining a stable posture. After each trial, feedback was provided on cognitive performance (number of correct items) and postural stability (COP area).

The study comprised up to three orientation sessions in the NBack task (30min each), followed by 11 practice sessions separated in two phases. Detailed information about the progression of the sessions and the tasks assessed in each one is presented in Table 1. In orientation sessions, participants started by performing the cognitive task only, for up to three sessions, to familiarize themselves with the task and to achieve 100% correct performance.

Up to three sessions were necessary to ensure that all older adults reached 100% correct performance. The task comprised 12 stimuli with an SOA of 2500 ms.

Insert Table 1 here

In the first phase (Sessions 1, 2, 4 and 5) the two tasks were performed concurrently, either on a stable platform (Sessions 1 and 4) or on a moving platform (Sessions 2 and 5). At the end of session 5 the cognitive task was assessed in a single-task context. In session 3 participants performed a functional stability boundary task in which their limits of stability were evaluated. In the above dual-task sessions, the cognitive task was always NBack-2 with a SOA of 2500 ms. In order to control for articulatory movements which cause an increase in postural instability (Yardley, Gardner, Leadbetter, & Lavie, 1999), in all dual-task sessions, single-task performance in posture was also assessed by naming the current digit starting at the first one presented (NBack-0), while standing on the platform. In dual-task sessions, participants performed A) two blocks of 2 single-task trials (posture and NBack-0), and B) two blocks of 2 dual-task trials (posture and NBack-2) in an A-B-B-A design. This order made sure that possible improvement over the course of the eight trials did not affect the single- vs. dual-task comparison.

After assessing **single-** and dual-task performance in NBack-2 in the first phase, in the second phase of the study the number of items in the working memory task was raised from NBack-2 to NBack-3 starting from Session 6. Posture tasks comprised the moving platform condition already used in the first phase of the study, as well as a condition with perturbations. To assess the influence of cognitive load in dual-task performance under conditions of comparable challenge for all participants and to avoid ceiling effects, task

difficulty (presentation rate) was individually adjusted. In addition, two levels of cognitive difficulty were introduced, low and high, by means of a longer or shorter SOA respectively. Low was the level of difficulty (SOA) at which participants were responding to all items correctly (100%), and high the level at which they were responding to 80% of the items correctly.

The two levels were established at Sessions 6 and 7, during which single-task performance was reassessed, using an adaptive testing procedure. SOA was gradually increased over the course of the two sessions from 2500 ms (12 items) to 1000 ms (30 items) at 6 levels of 4 trials each (2500, 2200, 1800, 1500, 1200 and 1000 ms). Testing stopped at the SOA at which participants reached an average of 80% correct performance, defined as the high difficulty level, and the nearest SOA in which they reached 100% correct, defined as the low difficulty level. Sessions 6 and 7 also included 4 single-task posture trials (moving platform), to maintain the level of postural stability obtained in the previous sessions. The two levels of cognitive difficulty established in session 7 were then used in three sessions examining dual-task performance in the most challenging conditions of the two tasks: cognitive NBack-3 and moving platform. Sessions 8, 9, and 10 were performed at an A-B-B-A design as described above for the previous dual-task sessions. In these sessions, two 8-trial blocks were performed, one for low and one for high cognitive difficulty. The final session (Session 11) included single-task (post-test) assessments of the cognitive task to evaluate performance improvement.

Data Analysis

Postural stability was assessed by fitting an 88% confidence ellipse to the Center Of Pressure (COP) trajectory using Principal Component Analysis. The two axes determined by

the two principal components were used as the two axes of the ellipse. The length of each axis was equal to 2 standard deviations of the COP trace along the axis, fitting 88% of the COP trajectory within the ellipse (Duarte & Zatsiorsky, 2002; Oliveira, Simpson, & Nadal, 1996). The ellipse area was used as the main measure of postural stability and was calculated using MATLAB (Mathworks, Natick, Mass., USA). Ellipse area measures were given a square root transformation before averaging to control for single trial outliers. Throughout the Results section we focus on data from conditions involving the sinusoidally moving platform, because this was the only posture task assessed throughout the full course of the study. Statistical analyses primarily comprised mixed-design Analyses of Variance (ANOVAs) with age as the between and session and context (single-task, dual-task) as within-subjects factors using SPSS (SPSS for Windows, Rel. 12.0.0. Chicago: SPSS Inc.).

Proportional DTCs, reflecting costs imposed on individual task performance in a dual-task setting were expressed as a percentage of single-task performance (proportional DTCs for cognition DTC_c , and posture DTC_p) according to the equations (for calculation details see Doumas, Smolders, & Krampe, 2008):

$$DTC_p = [(dual-task - single-task_p) / single-task_p] * 100 \quad (1)$$

$$DTC_c = [(single-task_p - dual-task) / single-task_p] * 100 \quad (2)$$

Results

We first present retest gains in single-task posture performance throughout the study. Second, we assess effects of cognitive load increase after initial practice. Third, we examine improvement in DTCs to assess effects of retest practice over and above improvements in single-task performance. Finally, we investigate task prioritization during retest practice predicted to be different in the two age groups.

Overall Improvement in Postural Stability

To assess our prediction for participants' overall improvement in postural stability with retest practice, we performed a mixed-design ANOVA on the COP ellipse areas fitted for single-task performance with Age (young, old) as between and Session (2, 5, 8, 9 and 10) as within-subject factors. Related measures are shown in Figure 1 with black and white circles denoting performance of young and older adults respectively. Overall, ellipse areas were smaller, that is, postural stability was greater in young adults from the start, and this difference was maintained throughout the study $F(1, 16) = 34.74, p < .01, \text{partial } \eta^2 = 0.69$. Both age groups showed improvement in postural stability (i.e., decrease in ellipse areas) over the course of practice, $F(4, 64) = 5.66, p < .01, \text{partial } \eta^2 = 0.26$, with overall practice gains being similar for young and older adults as shown by the lack of an Age by Session interaction $F(4, 64) = 0.896, p = .437, \text{partial } \eta^2 = 0.05$.

Insert Figure 1 here

Effects of Initial Practice and Increase in Cognitive Load

Working memory performance (NBack-2) in the first phase of the study (see Figure 2, left side) in both single- and dual-task (end of orientation sessions vs. end of Session 5) was at ceiling. Also in the first phase, in posture (see Figure 1, left side), overall, young adults had smaller areas than older adults as shown by a main effect of Age $F(1, 16) = 17.27, p < .01, \text{partial } \eta^2 = 0.52$, and stability had already improved in both age groups during Sessions 1-5 as shown by a main effect of Session $F(1, 16) = 6.25, p < .05, \text{partial } \eta^2 = 0.28$. Differences between single- and dual-task posture were not reliable and they did not interact with age,

presumably due to ceiling performance in the cognitive task or because older adults protected their postural stability or both.

In the beginning of the second phase of the study (Sessions 6 and 7) adaptive testing was applied to increase cognitive load, and to establish similar levels of working memory performance in the two age groups. Accuracy levels were checked at the end of Session 7, showing no reliable differences between the aimed 80% and 100% levels, thus, measures for the two levels were pooled. Individual adjustment was successful, leaving both age groups at similar levels well below ceiling at the first single-task assessment for NBack-3 in Session 7 (see Figure 2).

Insert Figure 2 here

To assess the effect of increased cognitive load (NBack-2 to NBack-3) in dual-task performance we contrasted postural stability (see Figure 1) in the final assessment of the first phase employing the NBack-2 task (Session 5) with the first assessment of the second phase using the more challenging NBack-3 task (Session 8). A mixed-design ANOVA with Age (young, old) as between- and Session (5, 8) and Context (single, dual) as within- subject factors revealed a main effect of Age, with young adults showing overall greater stability than older adults $F(1, 16) = 24.97, p < .01, \text{partial } \eta^2 = 0.61$. Older adults showed a substantial decrease in stability (increase in ellipse area) following changes in the cognitive task under dual- but not under single-task conditions (compare Fig. 1 Sessions 5, 8) while young adults continued to improve in both single- and dual-task conditions. This pattern was confirmed by reliable Session by Age $F(1, 16) = 9.22, p < .01, \text{partial } \eta^2 = 0.37$, Session by Context $F(1, 16) = 9.766, p < .01, \text{partial } \eta^2 = 0.38$, and Session by Age by Context interactions $F(1, 16) = 10.27, p < .01, \text{partial } \eta^2 = 0.39$.

Performance decrements in working memory due to concurrent posture demands were assessed after the increase in cognitive load (see Figure 2, right side) by contrasting single-task performance in NBack-3 (Session 7) with the first dual-task session performing NBack-3 (Session 8). Accuracies decreased reliably under dual-task conditions as shown by a main effect of Session $F(1, 16) = 13.22, p < .01$, partial $\eta^2 = 0.45$ and this decrease was similar in the two age groups.

In sum, young and older adults suffer similar losses in cognitive performance while performing a challenging working memory task and standing on the moving platform (see Figure 2, Session 7 vs. 8). However, increasing concurrent cognitive task load has substantial consequences for older adults' postural stability while young adults' stability remained basically unaffected (See Figure 1, Session 5 vs. 8). This finding gains additional theoretical significance by the fact that cognitive challenges were adjusted to comparable levels for young and older adults. As Figure 1 indicates, older adults accept additional sway (loss of stability) under dual-task conditions to a degree corresponding to the improvement in stability during the first phase (i.e. dual-task ellipse areas are similar for Sessions 2 and 8). This suggests reinvestment of practice gains to accommodate the increased cognitive challenges.

Increase in Cognitive Load and Improvement in Dual-Tasking: DTCs

Effects of the cognitive load increase discussed in the previous section can also be demonstrated at the level of proportional DTCs. A mixed-design ANOVA, contrasting DTCs in cognition (see Figure 3) before and after the cognitive load manipulation (Session 5 vs. 8) yielded reliable increases in costs $F(1, 16), = 5.58, p < .05$, partial $\eta^2 = 0.26$, which were similar for young and older adults. In other words, although before the cognitive load manipulation DTCs were almost zero, afterwards both young and older adults' cognitive

performance while standing on a moving platform was more than 10% less accurate than performing the task while seated. This effect emphasizes the effectiveness of the manipulation both in terms of increasing cognitive load in a dual-task setting, and in equalizing costs in the two age groups. In contrast, proportional DTCs in posture showed a different pattern (Figure 3). Although costs were similar in the two groups and near zero before the cognitive load manipulation, older adults' stability decreased by almost 20% when they performed the more difficult cognitive task, causing a reliable session by age interaction $F(1, 16) = 5.77, p < .05, \text{partial } \eta^2 = 0.27$, shown by the crossover in Figure 4, sessions 5 and 8.

Insert Figure 3 here

To assess retest practice in multi-tasking and its effects for both tasks (posture-cognition), we conducted a mixed-design ANOVA on proportional DTCs with task (cognition vs. posture) and Session (8, 9, and 10) as within- and age group (young, old) as between subject factors. Overall, older adults showed greater costs than young adults $F(1, 16) = 7.34, p < .05, \text{partial } \eta^2 = 0.31$, and a significant decrease in costs was observed with session $F(2, 32) = 7.47, p < .05, \text{partial } \eta^2 = 0.32$. These results, together with the absence of task differences, suggest that DTCs are similar in both tasks, and they decrease with practice at the same rate for young and older adults, as well as for posture and cognition as shown by the lack of interactions (in all cases $F < 1, p > .05$). While costs drop to zero and below in young adults, they remain reliably higher in both tasks for older adults even after three sessions of practice.

Insert Figure 4 here

Task prioritization During Retest Practice

The analyses above revealed that in both age groups proportional DTCs decrease with practice. With the final analysis we aim to assess the prediction that, with retest practice, older adults prioritize improvement in postural control, whereas young adults optimize cognitive performance. To assess this prediction, a direct contrast of dual-task improvement in the two tasks in sessions 8-10 was considered appropriate. This contrast cannot be performed using mean measures of performance due to the different metrics used (ellipse area and percent correct), thus, data from sessions 8-10 were transformed into Z-scores with $M = 0$ and $SD = 1$, standardized to the scores of each group in session 8. Because improvement in posture is expressed in performance decrease (smaller ellipse areas) Z-scores in posture were negative, thus they were rectified by multiplying by (-1). Figure 5 (left panel) depicts Z-gain scores for young adults, in which improvement was primarily observed in cognition, whereas the right panel shows that Z-gain scores for older adults revealing improvement primarily in posture. A mixed-design ANOVA with Age as between- and Session (8, 9 and 10) and Context (single vs. dual) as within-subjects factors confirmed these observations by showing a main effect of Session $F(1,16) = 5.406, p < .05$, partial $\eta^2 = 0.25$, and more importantly an Age by Session by Context interaction $F(2,32) = 2.734, p = .089$, partial $\eta^2 = 0.15$, which was reliable when a Helmert contrast was used, comparing session 8 and the average of sessions 9 and 10 $F(1,16) = 4.816, p < .05$, partial $\eta^2 = 0.23$. Pair wise t-tests between Z-gain scores of session 8 and the average of 9 and 10 confirmed our prediction for age differences in task prioritization by showing that young adults improved reliably in cognition, Mean Improvement = 1.103 SD, $t(7) = 4.149, p < .05$ but not in posture, whereas

older adults improved in posture, Mean Improvement = 0.67 SD, $t(9) = 3.382$, $p < .05$ but not in cognition.

Insert Figure 5 here

Discussion

The primary goal of the present study was to investigate older adults' potential for improvement in concurrent posture-cognition performance, first in the component tasks, but more importantly in dual-task performance. Our second goal was to investigate differences in the way young and older adults improved during dual-task performance. In terms of the component tasks (single-task), assessment of postural stability confirmed our prediction for substantial overall improvements in both young and older adults, with similar gains in the two age groups. After initial practice we implemented an increase in cognitive task load (from NBack-2 to NBack-3), while successfully adjusting individual task challenges at 80% correct through adaptive testing. As a result, dual-task costs increased in both groups with pronounced increases in older adults. Subsequently, we showed that both groups' elevated DTCs gradually dropped to zero through retest practice. As predicted, differential improvements during dual-task retesting showed that older adults prioritized stability whereas young adults' improvements were in cognition for the most part. In our view, these findings demonstrate the adaptive flexibility in older adults' resource allocation and a persistent potential to bring this flexibility to bear in challenging situations despite age-related constraints in resource availability. However, due to the possibility of a ceiling effect in young adults' posture, allowing little room for improvement in dual-task performance, the notion that young adults prefer cognition over posture remains open for debate.

Our findings for flexibility in resource allocation with task demands and practice have parallels with findings from previous studies (Brown, Sleik, Polych, & Gage, 2002; Doumas, Smolders, & Krampe, 2008; K. Z. H. Li, Lindenberger, Freund, & Baltes, 2001; Rapp, Krampe, & Baltes, 2006), which demonstrated that older adults prioritize sensorimotor over cognitive performance in challenging task contexts. Our study adds to the above findings because flexibility and prioritization were evaluated while postural stability was improving and cognitive task load was changing. Closer inspection of Figure 1 shows, that older adults' stability had already improved considerably during the first (NBack-2) phase of the experiment and their DTCs in posture and cognition were near zero. After the increase in cognitive task demands, dual-task costs in cognition increased by about 12% in both young and older adults, while DTCs in posture increased from zero to 20%, but only in older adults. While this pattern is seemingly at odds with the assumption of prioritizing posture, note that older adults' area of stability (ellipse area) essentially returned to levels observed in the beginning of practice (Figure 1). Presumably, improved stability by the end of the first phase had reduced resource demands for postural control in older adults, and in turn made resources available for facing the increased cognitive task challenges. Thus, practice allowed older adults to accept a 20% increase in sway, because they could nonetheless remain within their subjective safety area of stability.

The observed flexibility in older adults after practice gives reasons for optimistic perspectives on interventions aiming at fall prevention on the one hand and increasing older adults' cognitive potential through bodily exercise on the other (Kramer et al., 1999; Kramer & Willis, 2002). Naturally, the good news **applies** first and foremost to healthy, motivated older adults such as those willing to participate in a multi-session experiment like ours and it remains to be seen to which degree our findings generalize to other populations of older

adults. For example, the flexibility in resource allocation observed in this study was not present in posture-cognition dual-tasking in older adults with a history of falls (Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). When instability increases, older “fallers” continue to attempt to complete the cognitive task, instead of shifting resources from cognition to posture to maintain stability. Thus, it remains to be seen whether older fallers have the capacity to improve their postural stability in a dual-task context. However, in another **group of older adults**, patients with Alzheimer’s disease, flexibility is present in posture-cognition dual-tasking (Rapp, Krampe, & Baltes, 2006), suggesting that stable adaptations are shaped by everyday experiences rather than high level functions like executive control which is impaired in older adults and even more so in patients with Alzheimer’s disease.

Our study illustrates the considerable benefits of self-guided retest practice, that is, scheduled exercise with detailed feedback but without explicit instructions for improvement. Identifying related practice methods that help optimization of the learning progress in multi-tasking involving sensorimotor control through practice, is a challenge for future research.

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Footnote

¹Errors can occur in several ways: (a) if participants miss an item and stop responding momentarily, when they resume they will have missed a number of items; (b) if participants miss an item in NBack-3 and shift to NBack-2, they cannot correct their error immediately. Due to the diversity of errors and difficulties in tracking recovery attempts, we limited measurement to the number of correct responses until the first error.

Author note

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Table 1

Session structure. The dashed line separates the first and second phases of the study.

Session	Working Memory		Posture	
	Task	Context	Task	Context
Orientation	NBack-2	ST	--*	
Session 1	NBack-2	DT	Stable platform	ST and DT
Session 2	NBack-2	DT	Moving platform	ST and DT
Session 3	--*		FSB**	
Session 4	NBack-2	DT	Stable platform	ST and DT
Session 5	NBack-2	DT	Moving platform	ST and DT
Session 6	NBack-3	ST	--*	
Session 7	NBack-3	ST	--*	
Session 8	NBack-3	DT	Moving platform	ST and DT
Session 9	NBack-3	DT	Moving platform	ST and DT
Session 10	NBack-3	DT	Moving platform	ST and DT
Session 11	NBack-3	ST	--*	

Note. ST = Single-Task, DT = Dual-Task

*No assessment included

**FSB (Functional Stability Boundary) assesses tolerance for self-induced sway by having participants sway repeatedly along anterior–posterior, lateral, and two diagonal axes at their maximum ranges according to their subjective perception of safety. FSB was used as an indicator of maximum voluntary sway.

Figure captions

Figure 1. Single and dual-task performance in the dynamic posture task, in which the platform was rotating in the sagittal plane about the ankle joint axis, for young and older adults over the course of the study. Posture performance was measured as the area of an 88% confidence ellipse fitted on the COP trajectory (see text for details). Error bars in all figures show ± 1 standard error of the mean.

Figure 2. Single and dual-task performance in the NBack task for young and older adults, expressed as a percentage of correct items over the course of the study.

Figure 3. Proportional dual-task costs in cognition.

Figure 4. Proportional dual-task costs in posture.

Figure 5. Z-gain scores expressing improvement in dual-task performance in SD units for young and older adults in posture and cognition. Improvement of 1 in this metric reflects practice gain of 1 SD of session 8

Figure 1

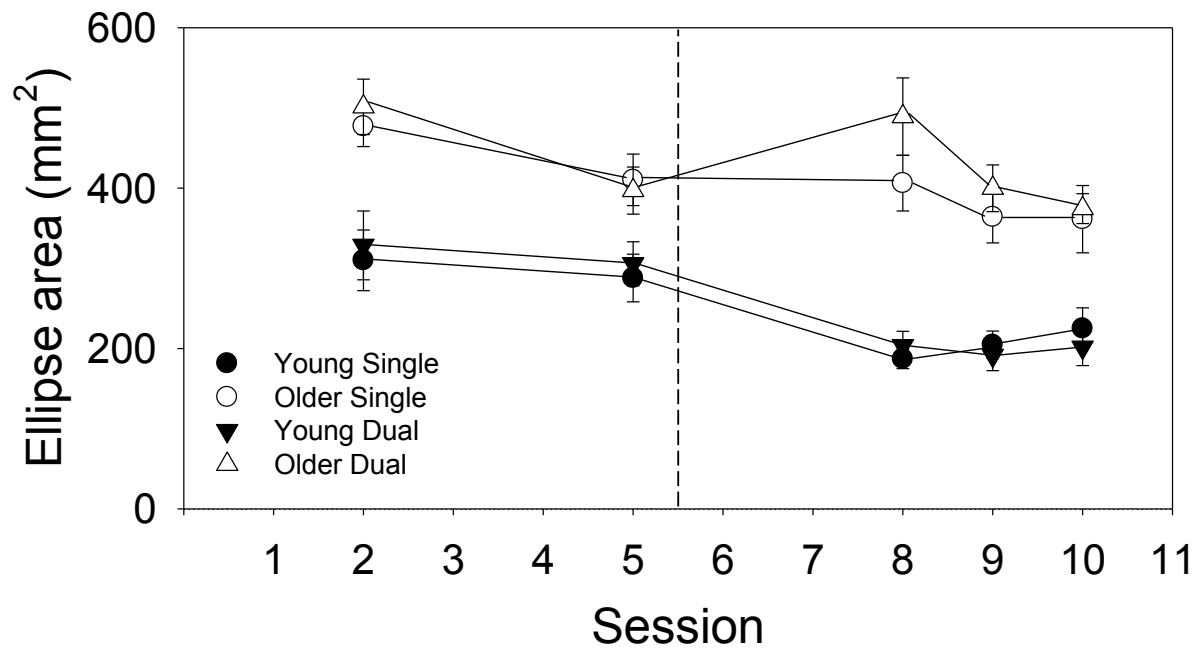


Figure 2

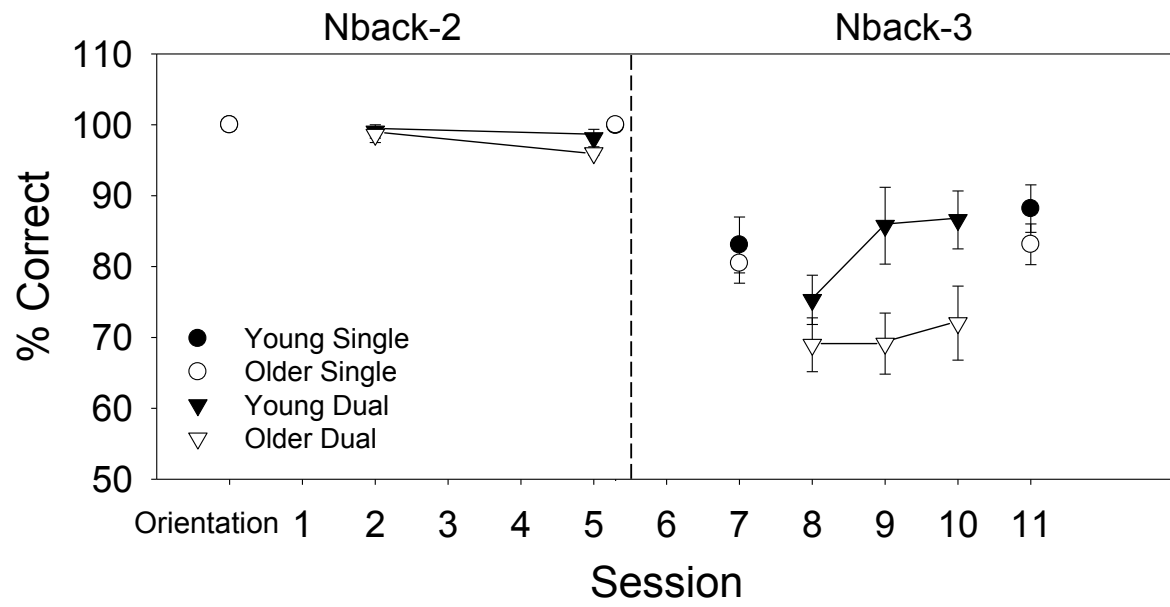


Figure 3

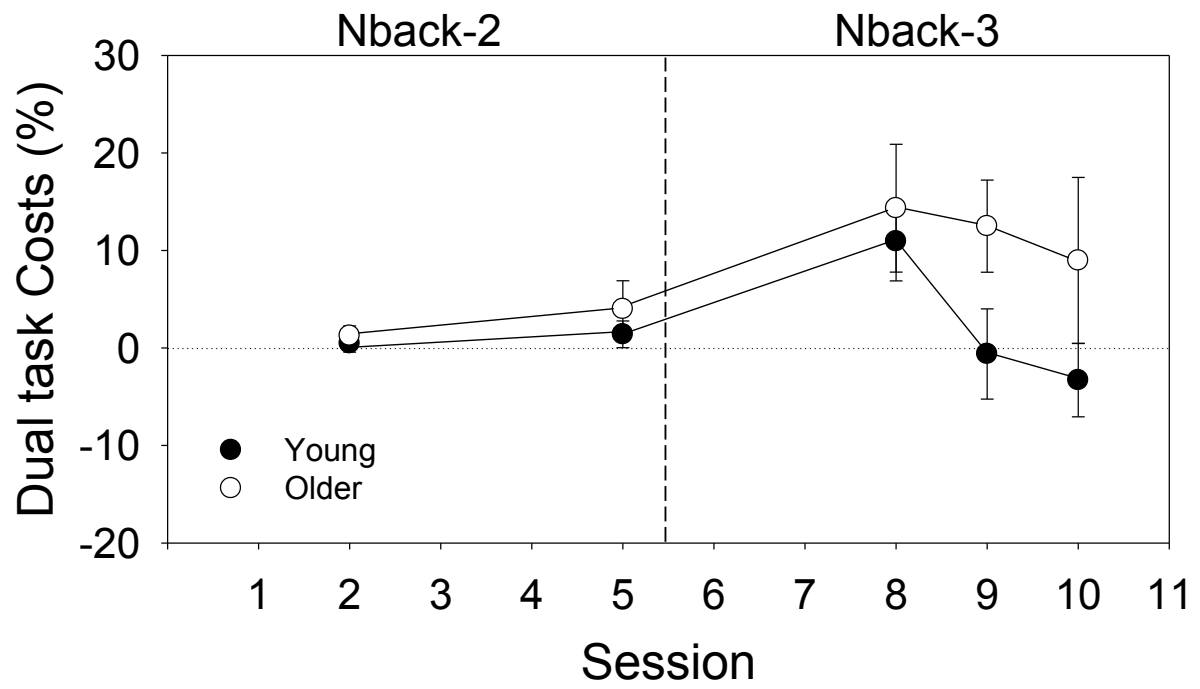


Figure 4

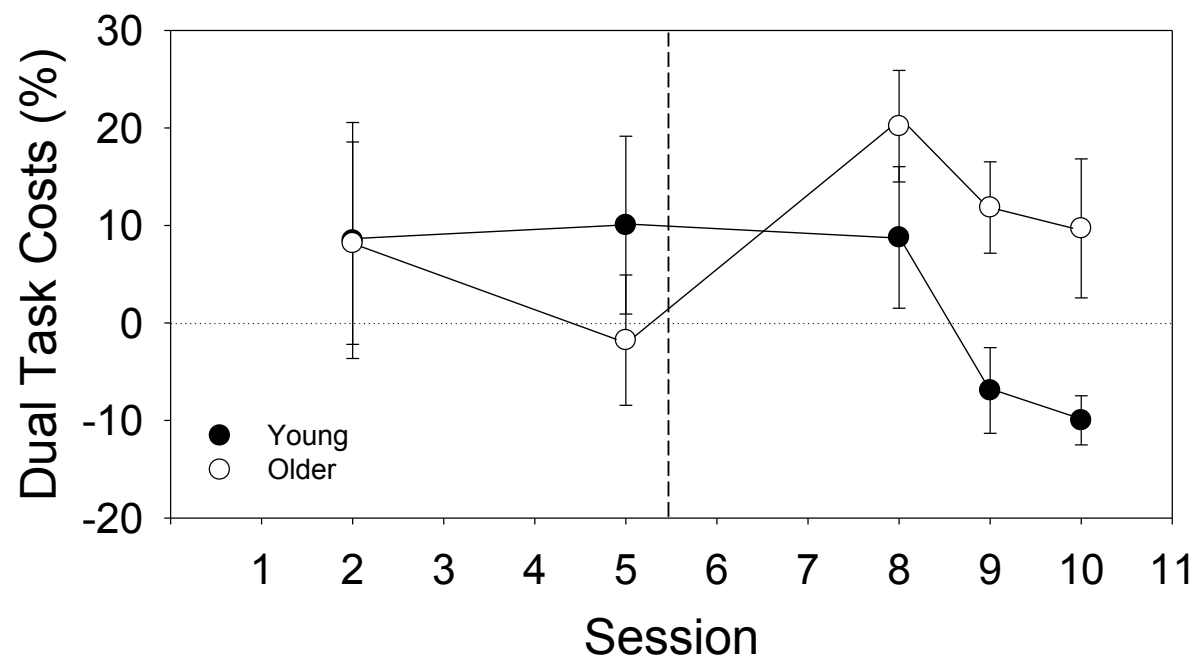


Figure 5

