Ecological Relevance Determines Task Priority in Older Adults' Multitasking

Drop that glass before you stumble: Ecological relevance determines task priority in older adults' multitasking

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Abstract

Objectives: Multitasking is a challenging aspect of human behaviour especially if the concurrently performed tasks are different in nature. Several studies demonstrated pronounced performance decrements (dual-task costs) in older adults for combinations of cognitive and motor tasks. However, patterns of costs among component tasks differed across studies and reasons for participants' resource allocation strategies remained elusive.

Methods: We investigated young and older adults' multitasking of a working memory task and two sensorimotor tasks, one with low (finger force control) and one with high ecological relevance (postural control). The tasks were performed in single-, dual- and triple-task contexts.

Results: Working memory accuracy was reduced in dual-task contexts with either sensorimotor task and deteriorated further under triple-task conditions. Postural and force performance deteriorated with age and task difficulty in dual-task contexts. However in the triple-task context with its maximum resource demands older adults prioritized postural control over both force control and memory.

Discussion: Our results identify ecological relevance as the key factor in older adults' multitasking.

Keywords: Multitasking, Aging, Sensorimotor Control, Postural Control, Dual Tasking, working memory

Introduction

Aging affects cognitive and motor task performance but it is especially evident in everyday activities requiring multitasking. For example at a busy party normally you are holding a drink while maintaining conversation and in many cases people are passing behind you disrupting your standing balance. In such activities people cannot pay attention to all tasks and this is especially the case for older adults due to age-related decline in cognitive and sensorimotor processing (Woollacott & Shumway-Cook, 2002). Instead, older adults are likely to prioritize one task, in this case standing balance because dropping a glass is not as critical as losing one's balance and falling. Thus, the priority given to different tasks during multitasking is likely to be determined by the task's importance for daily life, in other words the task's ecological relevance. In the present study we assessed age differences in multitasking of a memory task and two motor tasks different in terms of ecological relevance, namely finger force control and postural control. The main aim of the study was to investigate resource allocation dynamics in a challenging multitask setting and related differences between young and older adults.

There is little disagreement in the literature about the finding that older adults' sensorimotor and cognitive performance shows greater decline when a task is performed in dual- relative to single-task performance (for a review see Li, Krampe, & Bondar, 2005). Greater dual-task costs in older adults have been shown even in cases in which a cognitive task is performed concurrently with a seemingly effortless sensorimotor task like postural control (Doumas, Rapp, & Krampe, 2009; Doumas, Smolders, & Krampe, 2008; Maylor & Wing, 1996; Rapp, Krampe, & Baltes, 2006; Smolders, Doumas, & Krampe, 2010) or finger force control (Voelcker-Rehage &

Alberts, 2007; Voelcker-Rehage, Stronge, & Alberts, 2006). Such increases in dual-task costs have been observed in the form of performance decrements in the sensorimotor task (Maylor & Wing, 1996; Voelcker-Rehage & Alberts, 2007) and in both tasks (Shumway-Cook & Woollacott, 2000; Voelcker-Rehage et al., 2006).

The observed increase in dual-task costs with age has typically been interpreted to reflect cognitive capacity limitations (Kahneman, 1973). Both cognitive and sensorimotor performances require cognitive resources especially in older adults (Woollacott & Shumway-Cook 2002) and in dual-task performance older adults reach capacity limits sooner than young adults due to age related decline in cognitive processing.. However, recent studies have shown that it is possible for older adults to accommodate this decline by adaptively allocating their cognitive resources (Doumas et al., 2009; Doumas et al., 2008; Li et al., 2005; Li, Lindenberger, Freund, & Baltes, 2001; Rapp et al., 2006). These studies assessed older adults' cognitive-sensorimotor dual-task performance while experimentally manipulating sensorimotor task difficulty. For example, in two recent studies (Doumas et al., 2008; Rapp et al., 2006) participants performed a working memory task while standing on a stable platform (low difficulty) or on a moving platform (high difficulty). Young adults showed little or no dual-task costs to begin with, while older adults showed small costs in the cognitive task, but considerable costs in the sensorimotor task in the low-difficulty sensorimotor condition (stable platform). However, under conditions of high sensorimotor challenge (moving platform) during which postural instability increases, cognitive costs increased in older adults, while costs in the posture task were kept very low in young adults and hardly significant (Doumas et al., 2008; Rapp et al., 2006).

These findings suggest that during dual tasking older adults direct resources to the cognitive task if postural control is easy to achieve. However, when posture task difficulty increases they shift resources from cognition to posture thereby prioritizing postural stability to avoid instability and potential falls. Similar prioritization effects in older adults were demonstrated in tasks such as manipulations of postural threat (Brown, Sleik, Polych, & Gage, 2002) and memorization-walking dual-task performance (Li et al., 2001).

These authors attribute prioritization to the ecological relevance of tasks such as postural control and walking (Li et al., 2005). In our approach ecological relevance of a task comprises the following aspects: (1) the task's ecological validity, which is defined as its ability to capture important aspects of participants' daily lives even in a lab setting; (2) the degree to which combinations of tasks tested in the lab have equivalents in daily life (3) the functional and instrumental value that a task or a combination of tasks have for participants' daily lives. The latter aspect relates to the consequences of executing a task or not and to the quality of performance. Naturally, all three aspects depend on individual differences, like age: loss of postural stability can cause fall accidents, hip fractures and even accidental death in older adults (Tinetti & Williams, 1998). For an older person these consequences are far more serious than, for example, loss of monetary reward for performing a working memory task. In contrast, for young adults postural control is relatively effortless thus accurate performance of a cognitive task while standing is much easier.

However, a direct demonstration of the relation between ecological relevance and task prioritization is so far missing in the literature. A key problem with the ecological relevance argument is its inherent circularity, because notions of "relevance" or "higher relevance" of tasks for older adults rely on face plausibility or the observation of prioritization as such rather than independent assessment. For example, it would be plausible for prioritization to occur when older adults approach their limits of postural stability. However none of the participants in one of the aforementioned (Rapp et al., 2006) posture studies approached a fall during dual tasking as could be determined from their independently assessed functional stability boundaries. Depending on the study in question, prioritization has been demonstrated as within-group differences in dual-task costs, the absence of age differences in dual-task costs in the more challenging task, or the absence of reliable differences from zero for dual-task costs in older adults. From this perspective it seems unsurprising that increasing difficulty of the sensorimotor task led to prioritization in several, but certainly not all studies (Doumas et al., 2009; Kemper, Herman, & Lian, 2003; Smolders et al., 2010)

One potential alternative explanation for the observed allocation patterns is that overlearned sensorimotor tasks like posture and walking are less susceptible to deliberate cognitive control than cognitive tasks. Thus, such tasks may prove more robust against withdrawal of resources when competition among tasks becomes severe. Naturally, the latter situation is more likely to occur in older adults. Two empirical observations support this hypothesis: first, concurrent sensorimotor tasks tend to elicit higher dual-task costs (in both cognitive and sensorimotor performance) in older compared with young adults even if their ecological relevance seems small as for finger tapping (Krampe, Doumas, Lavrysen, & Rapp, 2010) or force control (Voelcker-Rehage & Alberts, 2007). Second, Alzheimer's patients show virtually the same prioritization patterns as healthy age-matched older adults deeming strategic allocation or higher cognitive executive control mechanisms an unlikely candidate mechanism for this type of adaptation (Rapp et al., 2006).

The only way to disentangle these issues and to provide direct evidence for the ecological relevance account is to pit resource demands of two sensorimotor tasks differing in ecological relevance against each other while both are competing for resources with an on-going cognitive task. To this end we investigated how young and older adults achieve multitasking of a task with high cognitive demands (working memory) and two sensorimotor tasks with different ecological relevance: finger force control (low) and postural control (high). Specifically, we used a dual- and triple-task paradigm (Figure 1) comprising a finger force task with two levels of difficulty (holding a force transducer between thumb and index finger at 5% and 20% Maximum Voluntary Contraction, MVC), a posture task with two levels of difficulty (standing on a stable or on a sway referenced surface), and a working memory task (nback, Dobbs & Rule, 1989). Task difficulty in the working memory task was individually adjusted to a sub-ceiling level (80%) in all participants using an adaptive procedure. This adjustment ensured that the task was performed at high difficulty, which in turn suggests that young and older adults invested the maximum amount of available cognitive resources. We assessed resource allocation dynamics of the two motor tasks directly in triple-task performance where we combined the n-back task with one of the conditions of each sensorimotor task. These conditions were chosen on the basis of previous studies showing large age differences: a sway referenced platform condition in postural control (Doumas et al., 2008) and 5% MVC which is the force level that is most sensitive to age-related decline (Vaillancourt, Larsson, & Newell, 2003).

Based on earlier studies we expected both sensorimotor tasks to elicit dual-task costs, which should be higher for older adults. Importantly, we predicted different patterns of costs for these two tasks depending on the sensorimotor task's ecological relevance and the level of induced resource competition, which increased from single- to dual- and finally triple-task contexts. The most informative pattern of resource allocation was expected in the transition from dual- to triple-task performance, where the two motor tasks directly compete for cognitive resources. For force control we predicted a gradual increase in variability, an effect presumably pronounced in older adults. In contrast, for posture control we predicted that when the induced resource shortage becomes severe in triple task, older adults would maintain a certain level of postural stability (i.e., not accept increases in multitask costs) to the expense of accuracy in both memory and force control.

Methods

Participants

Seventeen young and 14 older right-handed volunteers participated in the present study. Handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971). Inclusion criteria were no neurological or orthopaedic disorders, no falls in the last six months and no intake of medication known to affect postural control (Tillement et al., 2001). Participants had normal or corrected-to-normal vision. Screening tests included two marker tests from the WAIS (Wechsler, 1997), digit symbol substitution (DSS) and digit span (DS) and touch sensitivity for the hand and foot using Semmes-Weinstein monofilaments. Older adults showed reduced performance in DSS and DS as is common in this age group (Verhaeghen & Salthouse, 1997), as well as lower touch sensitivity for the hand and foot (Perry, 2006). Written informed consent was obtained in accordance with institutional ethics committee guidelines. Participants were paid 20 € for their participation. Characteristics of the participants are summarised in table 1.

Apparatus

The n-back task was implemented using auditory presentation of pre-recorded numbers (1-9) through a computer speaker (Figure 1A) using software custom-written in Labview (National Instruments). During force assessment (Figure 1B) participants grasped a cylindrical force transducer (Novatech F306) with the distal pads of the thumb and index finger of their dominant hand (Figure 1B). The transducer was mounted with two aluminium plates on either side. Its mass was 20g, the distance between grip surfaces 12mm and its diameter 38mm (Figure 1B inset). The transducer's output was amplified through a Novatech SY011V load cell amplifier at an excitation of 5V and was connected to a PC through a NI USB-6210 DAQ card (sampling frequency: 50Hz). Force output was displayed on a 17" computer screen (resolution: 1024x768 pixels), located 70cm in front of the participant and 100cm from the ground, in a panel spanning the width of the screen and approximately half the screen's height. The target force was displayed as a fixed red line in the middle of the panel and the produced force was displayed as a white trajectory that moved from left to right on the monitor. The y-axis scale was set to ±2N from the target force, and the system gain was set so that force of 1N corresponded to a vertical shift of the line of 100 pixels. Force was assessed in two conditions, 5% and 20% of each participant's MVC.

Postural control was assessed using the Neurocom Clinical Research System (NeuroCom International, Clackamas, OR) comprising two independent (23x46cm) 6df AMTI force plates and a 3-sided surround. Vertical forces applied on the force plates were recorded at a sampling frequency of 100 Hz and were used to derive the Center of Pressure (COP) time series in the Anterior Posterior (AP) and Mediolateral (ML) directions. During posture conditions participants wore a safety harness that was only engaged in the case of loss of balance, which never occurred in this experiment. Postural control was assessed in two conditions, stable (fixed) and sway referenced surface. Sway referencing was achieved using a servo-controlled motor, tilting the force plates in the pitch axis about the ankle joint in proportion to the participant's Center of Mass (COM) sway angles (Nashner, 1982; Nashner, Black, & Wall, 1982). When this proportion (or gain) is 1, COM sway of 1° results in 1° platform tilt, thereby inducing inaccurate proprioceptive information about body sway. In the present study we chose gain of 1.5 aiming to replicate previous findings showing age differences in postural stability using sway reference (Doumas et al., 2008).

Tasks

Single task performance in working memory was assessed using an auditory n-back task. Participants were asked to verbally repeat numbers presented in a fixed inter-stimulus interval (ISI) through the computer speaker two (2-back) or three (3-back) cycles before. Response accuracy was monitored by the experimenter and was defined as the percentage of successive correct responses until the first error.

During single task force control participants were asked to match the target force with the pinch force they exerted on the force transducer (Figure 1B). In posture tasks participants were asked to maintain stable standing posture on the platform and to maintain their gaze on a fixation cross located in front of them at eye level (Figure 1C). In single task performance of both force and posture participants were always performing a 0-back task, which included the verbalization but not the memory aspect of the n-back task in order to control for effects of verbalization that affects postural stability (Yardley, Gardner, Leadbetter, & Lavie, 1999) and may also affect force control. That way the only difference between single and dual task performance was working memory load.

Dual-task assessment included each of the four motor task conditions (5% MVC, 20% MVC, stable and sway reference) performed concurrently with the working memory task at the individually determined difficulty level (80% accuracy). During triple-task performance (Figure 1D) participants were standing on a sway-referenced platform, performing the working memory task at the 80% level and the force task at 5% MVC. In triple task the fixation cross was replaced by the feedback screen of the force task displayed in a monitor built in the system's 3-sided surround. Trials in all tasks lasted for 30s.

Procedure

The experiment was conducted during two sessions, no more than 10 days apart. Session 1 was designed to collect participant information from screening tests, to apply the adaptive testing procedure of the memory task and to familiarize participants with single-task performance of force and posture tasks. Working memory accuracy was individually adjusted by gradually increasing task difficulty, in order to achieve 80% correct performance in all participants. Three trials in each difficulty level were performed, starting with 2-back at inter-stimulus intervals (ISI) of 2200ms, 1800ms and 1400ms and then 3-back in the same ISIs. The level in which performance reached 80%

accuracy or lower was set as the individual performance level. Finally participants performed 5 single-task trials in each sensorimotor task condition.

In Session 2 single-, dual- and triple-task performance were assessed. Single-task working memory, posture and force tasks were performed in 3-trial blocks in the beginning and in the end of the session to control for practice and fatigue effects. Single task working memory was also assessed in the middle of the session in order to monitor participants' concentration over the course of the session. The four dual-task performance blocks (5% MVC-memory, 20% MVC-memory, stable-memory and sway reference-memory) included 5 trials each. Two of these blocks (one force-memory and one posture-memory) were performed after single-task assessment in the beginning and two (one force-memory and one posture-memory) before single-task assessment in the end. The order of these four dual-task blocks was counterbalanced. Triple-task performance (5% MVC–memory–sway reference) included 5 trials and was always performed after working memory assessment in the middle of the session to ensure that when this highly demanding condition was introduced participants were familiar with both single- and dual-task conditions.

Data analysis

We focus on results from the critical task conditions, performed in Session 2. Force-time trajectories, and AP and ML COP trajectories were first low-pass filtered using a 4^{th} order dual-pass butterworth filter with a cutoff frequency of 20Hz, and then data for the first 5 and last 2s in each trial were discarded. Force variability was measured using the Root Mean Squared Error (Vaillancourt & Newell, 2003). Postural stability was measured by fitting an ellipse to the COP trajectory using Principal Components Analysis (Duarte & Zatsiorsky, 2002; Oliveira, Simpson, & Nadal, 1996). These measures were calculated using MATLAB (Mathworks, Natick, Mass., USA). Force and posture data were given a square root transformation before averaging to control for single-trial outliers. Statistical analyses were performed using PASW 18 (SPSS: An IBM company).

Results

Comparisons of single- and dual-task performance

After the individual adjustment in memory task difficulty, performance levels for one young adult were determined at 2-back 1400ms and for all others at 3-back (1400ms, n=12; 1800ms, n=3 and 2200, n=1). In contrast, for 12 older adults difficulty was determined at 2-back (1400ms, n=5; 1800ms, n=7) and for 2 at 3-back 2200ms. Single- and dual-task working memory accuracy is depicted in Figure 2A. No differences were shown in single task memory accuracy in pre- mid- and post-test. In single task (Fig. 2A, left), accuracy in both groups was not reliably different from our target level of 80% as shown by separate one-sample t-tests for the two groups (M_{young}=80.22%, SD=11.56%, $t(16)=.79$, $P>.05$; M_{older}=74.85, SD=9.54, $t(13)=2.02$, $P>.05$). Together with the absence of reliable differences in accuracy between the two groups $t(29)=1.39$, $P>.05$ these results indicated that individual adjustment was successful. Figure 2A depicts effects of memory-force (Fig.2A middle) and memory-posture (Fig.2A right) dual-task performance on working memory. Two analyses of variance were performed to compare accuracy in single- and dual-task performance, one for memory-force and one for memory-posture with planned contrasts between single- and the mean of the two dual-task conditions. These contrasts showed that working memory accuracy decreased in dual-task performance with both force $F(3,27)=7.74$, $P<.05$, $\eta^2=.21$ and posture tasks $F(3,27)=5.45$, $P<.05$, $\eta^2=.16$ (Figure 2A). No other effects or interactions were significant.

Results for single- and dual-task performance in force (Figure 2B) and posture (Figure 2C) showed that force variability was greater in the 20% condition $F(1,29)=52.11$, $P<.01$, $\eta^2=.64$ and in dual-task performance $F(1,29)=5.31$, $P<.05$, $\eta^2=.16$. Older adults showed greater force variability compared with young but this effect only approached significance $F(1,29)=4.13$, $P=.051$, $\eta^2=.13$. Furthermore variability was greater in older relative to young adults especially in dual-task performance as shown by a context by age interaction $F(1,29)=5.92$, $P<.01$, $\eta^2=.17$ and more importantly, in older adults dual-task performance resulted in an increase in variability at 5% followed by an even greater increase in 20% whereas in young adults variability increased at 5% but decreased at 20% as shown by a task difficulty by context by age interaction $F(1,29)=7.82$, $P<.05$, $\eta^2=.21$].

A similar pattern of results was observed in postural control (Figure 2B). Ellipse areas were greater in the sway reference condition $F(1,29)=76.89$, $P<.01$, $\eta^2=.73$, in dual-task performance $F(1,29)=8.71$, $P<.05$, $\eta^2=.23$ and in older adults $F(1,29)=27.78$, $P<.01$, $\eta^2=.49$. Both task difficulty and dual tasking affected older adults more than young as shown by a task difficulty by age $F(1,29)=30.27$, $P<.01$, $\eta^2=.51$ and a context by age $F(1,29)=20$, $P<.01$, $\eta^2=.41$ interaction. More importantly a three way task difficulty by context by age interaction showed that older adults showed an increase in ellipse area in both difficulty levels whereas young adults showed an increase in stable but a decrease in sway reference $F(1,29)=5.01$, $P<.05$, $\eta^2=.15$. In summary, as predicted dual tasking with both motor tasks affected performance and these effects were greater in older adults especially as task difficulty increased. This pattern was similar in memory-force and memory-posture dual-task performance.

Triple-task performance

Triple-task conditions involved the simultaneous performance of working memory (80% adjusted), force (5% MVC), and posture (sway reference) tasks. Accuracy in the working memory task (Figure 3A) was assessed using a 4x2 mixed design analysis of variance with multitasking (single task, dual task with force, dual task with posture, triple task) as within- and age as between-subjects factors. Accuracy decreased with multitasking from near 80% in single-task to near 60% in triple-task performance $F(2.6,74.2)=9.77$, $P<.01$, $\eta^2=.25$ and no effects or interactions involving age were observed.

Likewise, force variability (Figure 3B) increased with multitasking demands $F(1.8,51.21)=8.59$, $P<.01$, $\eta^2=.23$ and was greater in older adults $F(1,29)=4.26$, $P<.5$, $\eta^2=.13$. In contrast, ellipse area (Figure 3C) decreased with multitasking $F(1.7,48.29)=10.13$, $P<.01$, $\eta^2=.26$ and was greater in older adults $F(1,29)=33.82$, $P<.01$, $\eta^2=.54$. The pattern in Figure 3C shows that in young adults multitasking demands caused a decrease in ellipse area reflecting greater stability but in older adults this effect occurred at the higher levels of cognitive and sensorimotor processing induced by triple-task performance. This increase in multitask load caused an ellipse area reduction to levels below single task as shown by an age by multitasking interaction $F(1.7,48.29)=7.96$, $P< .01$, $\eta^2=.22$]. Pair-wise t-tests showed that in young adults ellipse areas in dual- and triple-task performance were smaller than in single task [single vs. dual $t(16)=3.60$; single vs. triple $t(16)=3.71$, $P<.01$], but no differences were shown between dual and triple task. In older adults ellipse areas in single- and triple-task performance were not different, but were both smaller than in dual task [single vs. dual $t(13)=2.54$, $P=0.025$; dual vs. triple $t(13)=3.12$, $P<.01$].

Dual- and triple-task costs

Proportional dual- and triple-task costs were then calculated (for calculation details see Doumas et al. 2008) in order to quantify the percent change in performance between single- and dual-, and single- and triple-task performance. This metric provides a clearer picture on how both age groups accommodate the challenges introduced by task difficulty increases within each task and by task complexity introduced in dual- and triple-task performance. Specifically, we calculated proportional costs for force at 5% MVC (single- vs. dual and single vs. triple task performance), for posture in the sway reference condition (single- vs. dual and single vs. triple task performance) and for working memory (single- vs. dual-task with force at 5%, single- vs. dual-task with posture in the sway reference condition, and single- vs. triple-task with both motor tasks).

In working memory, dual-task costs were pooled between the first two contexts because no differences were observed between these contexts. Dual- and triple-task costs for these tasks are depicted in Figure 4. In young adults (Figure 4A) costs differed reliably from zero in posture (dual $t(16)=5.18$; triple: $t(16)=8.01$, both $P<.01$), in force (dual $t(16)=4.23$; triple $t(16)=4.83$, both $P<.01$) and in memory but only in triple task performance $t(16)=3.19$, $P<.01$. In older adults (Figure 4B) costs differed reliably from zero in posture only in dual task $t(13)=5.18$, $P<.05$), in force in both dual $t(13)=2.68$ and triple task $t(13)=3.42$, both $P<.05$ and in memory but only in triple task performance $t(16)=3.2$, $P<.01$. Differences in costs were assessed using a 2x3x2 mixed design analysis of variance with context and task as within- and age as between subjects factors, including two a-priori contrasts, one contrasting memory costs with the mean of the two sensorimotor task costs and one contrasting costs between the two sensorimotor tasks. Results for the main analysis showed that triple-task context caused greater costs than dual [dual: 20.76%, triple: 36.13%; $F(1,29)=5.5$, $P<.05$,

η^2=.16]. In young adults costs increased from 7.45% (dual) to 39.29% (triple) whereas in older adults costs remained at a similar level 34.07% (dual) to 32.96% (triple) as shown by a context by age interaction F(1,29)=6.33, P<.05, η^2=.18. Results for the first contrast showed that sensorimotor task costs were greater than memory costs F(1,29)=8.584, P<.05, η^2=.22. Sensorimotor costs increased in young adults but decreased in older from dual to triple task as shown by a task by context by age interaction F(1,29)=6.39, P<.05, η^2=.18. Results for the second contrast showed that force costs were greater than posture costs F(1,29)=54.81, P<.05, η^2=.62 and a task by context interaction showed that when multitask demands increased force costs increased but posture costs decreased F(1,29)=15.41, P<.05, η^2=.35. As a final step we performed pair-wise t-tests which showed that in young adults costs increased reliably from dual to triple task only in force t(16)=3.42, P=0.004 and in older adults showed an increase in memory t(13)=2.9, P=.013 and a decrease in posture t(13)=3.96, P=.001.

Discussion

The main aim of the present study was to investigate age differences in resource allocation dynamics between young and older adults. Multitasking was assessed during concurrent performance of a task with high cognitive demands (working memory) and two sensorimotor tasks with different levels of ecological relevance: finger force control (low) and postural control (high). Both sensorimotor tasks elicited costs in dual-task contexts. As a general trend, working memory performance gradually decreased as multitasking demands increased. Our key finding was that as multitask demands increased older adults prioritized postural control over both force control and memory. Specifically, we showed that in going from dual- to triple-task contexts both age groups showed performance decrements in the force control task as shown in differences in proportional costs, however, older adults actually improved their postural stability. In other words, they prioritized the ecologically more relevant sensorimotor task (posture) over the less relevant one (grip force).

The flexibility of resource allocation in our older participants corresponds with earlier findings by Kramer and colleagues who showed that older adults were as good as young adults in implementing differential emphasis patterns in attending to two concurrent tasks (Kramer, Larish, & Strayer, 1995) or switching between them (Kramer, Larish, Weber, & Bardell, 1999). Even though ecologically valid multitasking experiments like the one described in our study differ from the highly controlled experiments by Kramer and colleagues, both approaches emphasize the remarkable flexibility in older adults' resource allocation. The novel aspect of our study is that we can rule out differences in controllability between sensorimotor tasks on the one hand and cognitive tasks on the other as causes for allocation patterns. Instead, our evidence points directly to the task's ecological relevance as the key factor when resources become tight.

When contrasting age differences in multitask performance in our study it is important to consider that young and older adults were operating at different levels of resource constraints. In this regard our analyses of dual- and triple-task costs illustrate that multitasking is not a zero-sum game. In young adults we observed 6% dual-task costs increasing to 38% costs in triple task, not far from the 33% found in older adults. Different from young adults, dual (34%) and triple-task costs (33%) were statistically indistinguishable in older adults. This pattern suggests that young adults' performance was largely unaffected in dual-task conditions and they were able to perform all tasks with minimal performance decrements. In contrast, older adults showed sizeable performance decrements during dual tasking presumably reaching serious resource limitations and could not accept further increases in postural sway. The adaptive solution to this situation was to trade costs between sensorimotor tasks and to adopt a larger safety margin for the ecologically most relevant challenge. This finding can be explained with the general resource idea, however, young adults only encountered serious limitations when moving to triple-task performance, and they showed a decrease in postural sway with multitasking. This facilitation cannot be explained simply by changes in resource allocation.

Postural facilitation during posture-cognitive dual tasking in young adults is a well-documented but not consistent finding that has received several interpretations in recent studies (for review see Fraizer & Mitra, 2008). One view that may account for our findings suggests that there is a systematic facilitation occurring in young adults' postural sway as cognitive task difficulty increases (Huxhold, Li, Schmiedek, & Lindenberger, 2006). In this study, when young adults performed quiet standing with a focus of attention on posture, postural sway was high; however when cognitive task difficulty increased sway decreased similar to our results for multitask difficulty. This result suggests that following an increase in task difficulty, resources were directed away from posture and the task became more automatic, causing a reduction in sway. This interpretation can account for our results in young adults, with the increase in multitasking directing resources away from posture, making it more automatic thereby causing the observed reduction in sway.

It is important to acknowledge that our findings might have been different if we had chosen a grip force task with greater ecological relevance, for example, if participants were told to imagine holding a full glass of expensive wine, a valuable, fragile object or a small child. Under such circumstances, it is possible that they may risk a fall in order to ensure the child's safety. We assume that individual attributions and motives form a part of the task context and as such can influence priorities in multitasking. A limitation of our study is that by pitting two sensorimotor tasks against each other that differ in terms of "inherent" relevance, important questions about prioritization in other contexts remain unanswered. For example, individual differences like gender might determine priorities and processing load or age-related decline in capacity might constrain prioritization. We consider our study as a stepping-stone in approaching these questions, which should be systematically investigated by future research.

In conclusion, concurrent performance of multiple tasks is increasingly constrained by diminishing processing resources in older adults. Adaptive resource allocation specifically tuned to the ecological relevance of component tasks remains at older individuals' disposal and can thus partly attenuate and compensate for the negative effects of capacity limitations. Optimal aging and related interventions should not only foster the maintenance of resources but also promote adaptive allocation strategies implementing ecological relevance principles.

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References

Brown, L. A., Sleik, R. J., Polych, M. A., & Gage, W. H. (2002). Is the prioritization of postural control altered in conditions of postural threat in younger and older adults? *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 57*(12), M785-792.

Dobbs, A. R., & Rule, B. G. (1989). Adult age differences in working memory. *Psychology and Aging, 4*, 500-503.

Doumas, M., Rapp, M. A., & Krampe, R. T. (2009). Working Memory and Postural Control: Adult Age Differences in Potential for Improvement, Task Priority, and Dual Tasking. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 64*(2), 193-201.

Doumas, M., Smolders, C., & Krampe, R. T. (2008). Task prioritization in aging: effects of sensory information on concurrent posture and memory performance. *Exp Brain Res, 187*(2), 275-281.

Duarte, M., & Zatsiorsky, V. M. (2002). Effects of body lean and visual information on the equilibrium maintenance during stance. *Experimental Brain Research, 146*(1), 60-69.

Fraizer, E. V., & Mitra, S. (2008). Methodological and interpretive issues in posture-cognition dual-tasking in upright stance. *Gait & Posture, 27*(2), 271-279. doi: Doi 10.1016/J.Gaitpost.2007.04.002

Huxhold, O., Li, S. C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: Aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin, 69*(3), 294-305. doi: Doi 10.1016/J.Brainresbull.2006.01.002

Kahneman, D. (1973). *Attention and effort*. Engelwood Cliffs, NJ: Prentice-Hall.

Kemper, S., Herman, R. E., & Lian, C. H. T. (2003). The costs of doing two things at once for young and older adults: Talking while walking, finger tapping, and ignoring speech or noise. *Psychology and Aging, 18*(2), 181-192.

Kramer, A. F., Larish, J. F., & Strayer, D. L. (1995). Training for attentional control in dual-task settings: A comparison of young and old adults. *Journal of Experimental Psychology: Applied, 1*, 50-76.

Kramer, A. F., Larish, J. F., Weber, T. A., & Bardell, L. (1999). Training for executive control: Task coordination strategies and aging. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII. Cognitive regulation of performance: Interaction of theory and application* (pp. 617 – 652). Cambridge, MA: The MIT Press.

Krampe, R. T., Doumas, M., Lavrysen, A., & Rapp, M. (2010). The Costs of Taking It Slowly Fast and Slow Movement Timing in Older Age. *Psychology and Aging, 25*(4), 980-990. doi: Doi 10.1037/A0020090

Li, K. Z. H., Krampe, R. T., & Bondar, A. (2005). An ecological approach to studying aging and dual-task performance. In R. W. Engle, G. Sedek, U. von Hecker & D. N. McIntosh (Eds.), *Cognitive limitations in aging and psychopathology* (pp. 190-218). New York: Cambridge University Press.

Li, K. Z. H., Lindenberger, U., Freund, A. M., & Baltes, P. B. (2001). Walking while memorizing: A SOC study of age-related differences in compensatory behavior under dual-task conditions. *Psychological Science, 12*, 230-237.

Maylor, E. A., & Wing, A. M. (1996). Age differences in postural stability are increased by additional cognitive demands. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 51*(3), P143-154.
Nashner, L. M. (1982). Adaptation of Human Movement to Altered Environments. *Trends in Neurosciences, 5*(10), 358-361.
Nashner, L. M., Black, F. O., & Wall, C. (1982). Adaptation to Altered Support and Visual Conditions during Stance - Patients with Vestibular Deficits. *Journal of Neuroscience, 2*(5), 536-544.
Oliveira, L. F., Simpson, D. M., & Nadal, J. (1996). Calculation of area of stabilometric signals using principal component analysis. *Physiological Measurement, 17*(4), 305-312.
Perry, S. D. (2006). Evaluation of age-related plantar-surface insensitivity and onset age of advanced insensitivity in older adults using vibratory and touch sensation tests. *Neuroscience Letters, 392*(1-2), 62-67.
Rapp, M. A., Krampe, R. T., & Baltes, P. B. (2006). Adaptive task prioritization in aging: Selective resource allocation to postural control is preserved in Alzheimer disease. *American Journal of Geriatric Psychiatry, 14*(1), 52-61.
Shumway-Cook, A., & Woollacott, M. (2000). Attentional demands and postural control: the effect of sensory context. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 55*(1), M10-16.
Smolders, C., Doumas, M., & Krampe, R. T. (2010). Posture and cognition interfere in later adulthood even without concurrent response production. *Human Movement Science, 29*(5), 809-819.
Tillement, J. P., Albengres, E., Cottin, D., Klouz, A., Arkoub, H., & Le Louet, H. (2001). [The risk of falling due to benzodiazepine administration, alone or in combination, in elderly subjects]. *Therapie, 56*(4), 435-440.
Tinetti, M. E., & Williams, C. S. (1998). The effect of falls and fall injuries on functioning in community-dwelling older persons. *Journals of Gerontology Series a-Biological Sciences and Medical Sciences, 53*(2), M112-M119.
Vaillancourt, D. E., Larsson, L., & Newell, K. M. (2003). Effects of aging on force variability, single motor unit discharge patterns, and the structure of 10, 20, and 40 Hz EMG activity. *Neurobiology of Aging, 24*(1), 25-35. doi: Pii S0197-4580(02)00014-3

Doi 10.1016/S0197-4580(02)00014-3
Vaillancourt, D. E., & Newell, K. M. (2003). Aging and the time and frequency structure of force output variability. *Journal of Applied Physiology, 94*(3), 903-912.
Verhaeghen, P., & Salthouse, T. A. (1997). Meta-analyses of age-cognition relations in adulthood: Estimates of linear and nonlinear age effects and structural models. *Psychological Bulletin, 122*(3), 231-249.
Voelcker-Rehage, C., & Alberts, J. L. (2007). Effect of motor practice on dual-task performance in older adults. *The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences, 62*(3), P141-148.
Voelcker-Rehage, C., Stronge, A. J., & Alberts, J. L. (2006). Age-related differences in working memory and force control under dual-task conditions. *Neuropsychology, development, and cognition. Section B, Aging, neuropsychology and cognition., 13*(3-4), 366-384.
Wechsler, D. (1997). *Wechsler Adult Intelligence Scale (3rd ed.)*. San Antonio (TX): The Psychological Corporation.

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait and Posture, 16*(1), 1-14. doi: S0966636201001564 [pii]

Yardley, L., Gardner, M., Leadbetter, A., & Lavie, N. (1999). Effect of articulatory and mental tasks on postural control. *Neuroreport, 10*(2), 215-219.

Table 1. *Sample Characteristics: group means and standard deviations (in brackets)*

	Young adults	Older adults
Age	23.72 (4.03)	72.12 (3.07)
Sex (male, female)	5, 12	4, 10
Tactile sensitivity hand (score/5)	4.36 (0.56)	3.74 (0.35)*
Tactile Sensitivity foot (score/5)	4.60 (1.16)	2.78 (0.91)*
DS Forward (items)	10.18 (1.81)	8.64 (1.22)*
DS Backward (items)	7.41 (2.37)	6.43 (1.60)*
DSS s/item	1.27 (0.13)	1.74 (0.35)
MMSE	Not Applicable	29.38(1.35)
MVC (N)	51.2 (11.1)	52.3 (13.1)

DS: Digit Span,; DSS: Digit Symbol Substitution; MMSE: Mini Mental State Examination; MVC: Maximum Voluntary Contraction; *$P<.05$

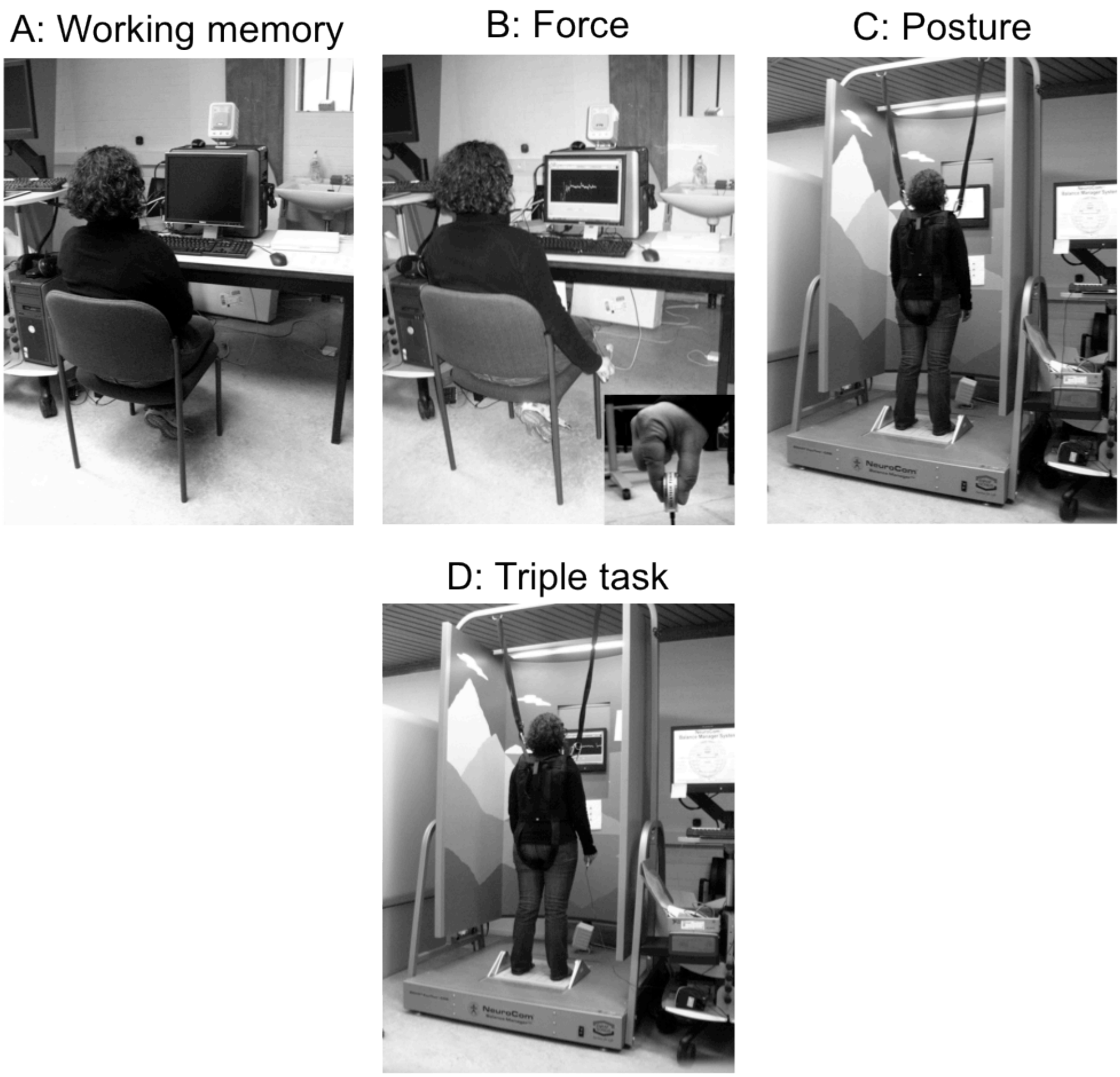

Figure 1. Task conditions in single-, dual- and triple-task performance. **A:** Single task working memory. **B:** Single task force. Inset (bottom right): Grip configuration. **C:** Single task posture. **D:** Triple task performance.

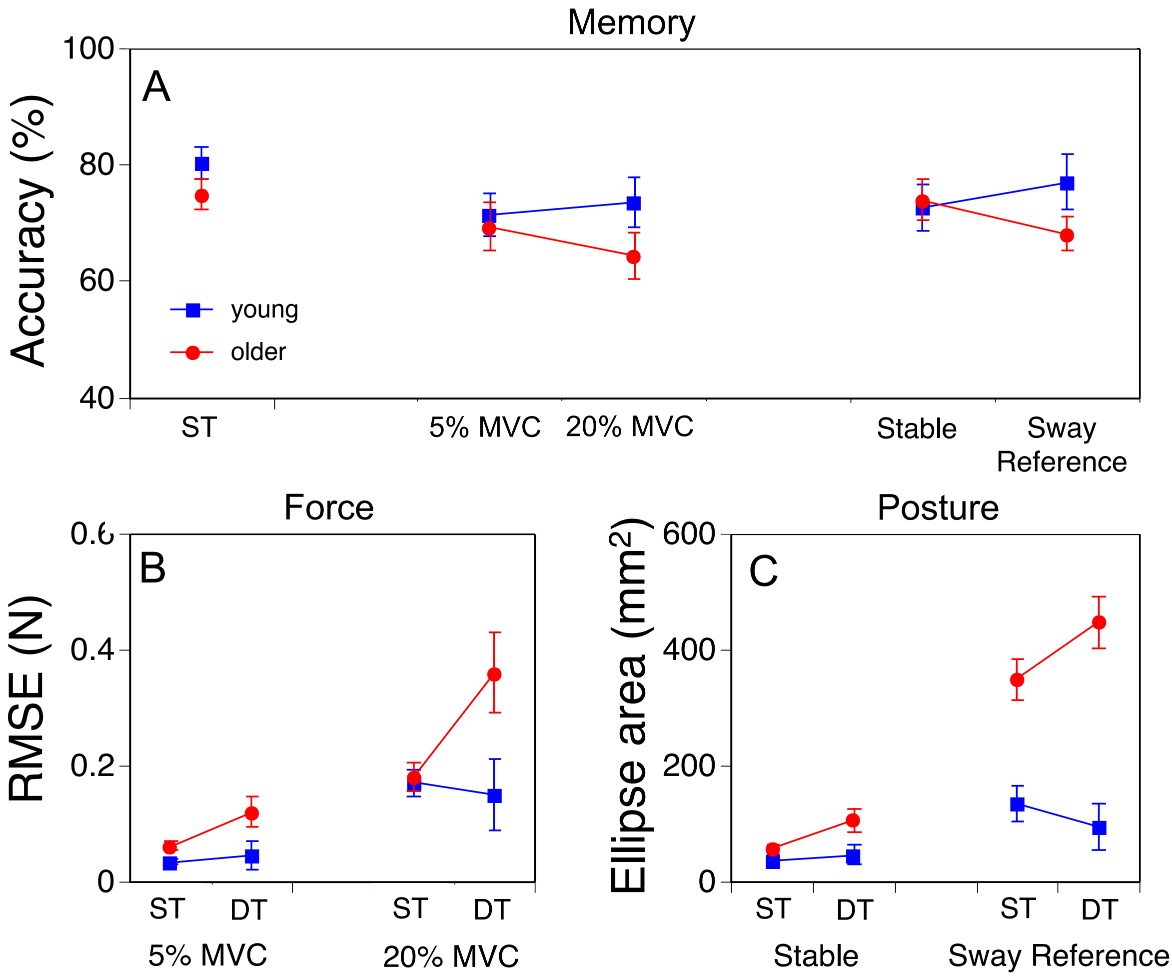

Figure 2. Single-Task (ST) and Dual-Task (DT) performance in young and older adults in the three tasks A: Working memory accuracy, B: Force variability measured as the Root Mean Squared Error (RMSE) and C: Postural stability measured as the ellipse area. Note that performance decrements are expressed as a decrease in accuracy in A, but in an increase in RMSE and ellipse area in B and C because the latter are measures of variability. Error bars represent 1 Standard Error of the Mean (SEM).

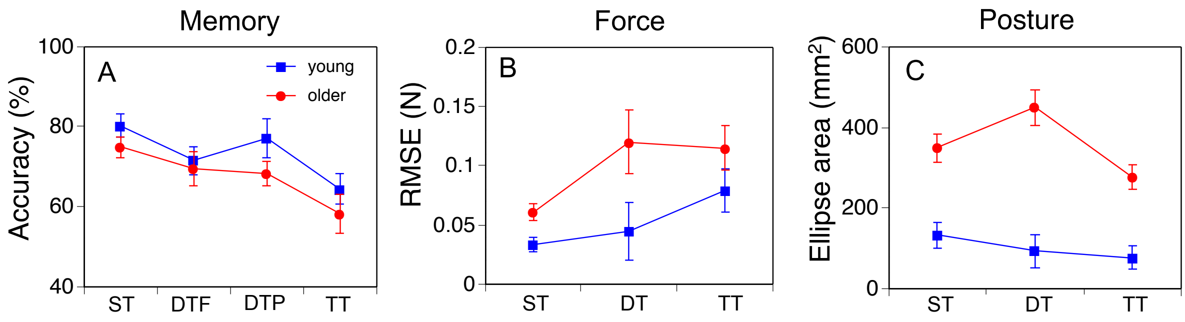

Figure 3. Single-Task (ST), Dual-Task (DT) and Triple-Task (TT) performance in young and older adults in the three tasks A: Working memory accuracy, B: Force variability and C: Postural stability. Note that in A, in dual-task performance the two middle data points reflect dual tasking of working memory and force at 5% MVC (DTF) and dual tasking of working memory and posture sway reference (DTP). Error bars represent 1 SEM.

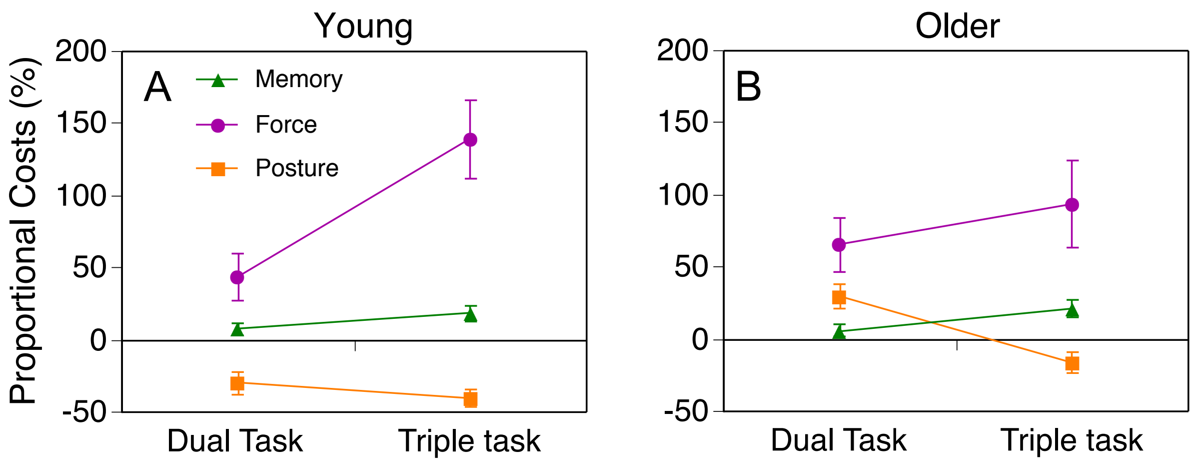

Figure 4. Dual- and triple-task costs in A: young and B: older adults. Both dual and triple task costs were standardized by the same single-task performance measures. Error bars represent 1 SEM.