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Effects of aging on the relationship between cognitive demand and step variability during dual-task walking

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Keywords

Aging, Gait, Cognitive control, Step variability, Resource competition

Abstract

A U-shaped relationship between cognitive demand and gait control may exist in dual-task situations, reflecting opposing effects of external focus of attention and attentional resource competition. The purpose of the study was twofold: to examine whether gait control, as evaluated from step-to-step variability, is related to cognitive task difficulty in a U-shaped manner and to determine whether age modifies this relationship. Young and older adults walked on a treadmill without attentional requirement and while performing a dichotic listening task under three attention conditions: non-forced (NF), forced-right (FR), and forced-left (FL). The conditions increased in their attentional demand and requirement for inhibitory control. Gait control was evaluated by the variability of step parameters related to balance control (step width) and rhythmic stepping pattern (step length and step time). A U-shaped relationship was found for step width variability in both young and older adults and for step time variability in older adults only. Cognitive performance during dual tasking was maintained in both young and older adults. The U-shaped relationship, which presumably results from a trade-off between an external focus of attention and competition for attentional resources, implies that higher-level cognitive processes are involved in walking in young and older adults. Specifically, while these processes are initially involved only in the control of (lateral) balance during gait, they become necessary for the control of (fore-aft) rhythmic stepping pattern in older adults, suggesting that attentional resources turn out to be needed in all facets of walking with aging. Finally, despite the cognitive resources required by walking, both young and older adults spontaneously adopted a “posture second” strategy, prioritizing the cognitive task over the gait task.

Introduction

Aging is associated with decrements in both executive functions, also called executive control or cognitive control (Diamond [2013](#)), and gait control as evaluated from the variability of gait patterns (Buzzi et al. [2003](#); Owings and Grabiner [2004](#); Kang and Dingwell [2008](#)). In older adults, interference caused by competing demands for attentional resources has been demonstrated when gait is performed simultaneously

with a cognitive task (i.e., dual-task paradigm). Studies have reported either increased step-to-step variability of gait parameters (e.g., step velocity, step time, and step length) or cognitive performance decrements under dual-task conditions (Beauchet et al. [2005a](#); Dubost et al. [2006](#); Hollman et al. [2007](#)). The decline in performance of either gait or cognitive processing relative to either task performed alone gives evidence that the concurrent tasks compete for attentional resources with aging. Importantly, the dual-task-related changes in gait variability were found to be predictors of falls in older adults (Kressig et al. [2008](#); Herman et al. [2010](#)). However, not all studies reported such age-related interference effects in dual-task walking (Yogev et al. [2005](#); Springer et al. [2006](#)). A mixed pattern of findings has also been seen in healthy young adults. Some studies showed no dual-task-related changes in gait variability, suggesting that the regulation of gait patterns proceeds without cognitive control (Beauchet et al. [2005b](#)), while others found either detrimental (i.e., increased gait variability) or beneficial (i.e., decreased gait variability) effects (Grabiner and Troy [2005](#); Dubost et al. [2008](#)). Thus, the association between cognitive control and gait variability and its changes with aging appear complex. Providing a model framework for these issues is important for future studies and for developing interventions that may reduce the negative impacts of dual tasking on fall risk.

A dual-process account of cognitive-motor interactions including opposing effects of “external focus of attention” and “attentional resource competition” on gait variability may account for the above mixed findings (Lövdén et al. [2008](#); Verrel et al. [2009](#)). Simple cognitive tasks would shift the focus of attention away from gait control, thus reducing top-down cognitive (or attentional executive) control of gait (i.e., decreased gait variability). Indeed, low variability often indicates processes that proceed with little cognitive control (Newell and Corcos [1993](#); Hausdorff [2005](#)). Inversely, higher levels of cognitive task difficulty would alter gait control (i.e., increased gait variability) through attentional resource competition (Li and Lindenberger [2002](#); Schaefer et al. [2006](#)). The two processes would trade off at lower levels of task difficulty in older adults, presumably as a result of age-related increased reliance on higher-level cognitive processes for gait control (i.e., less automaticity), coupled with reduced cognitive control efficiency (Seidler et al. [2010](#)). However, empirical support for this model remains insufficient. Studies either failed to detect a clear trade-off between the two processes with increasing cognitive control demand in older adults (Lövdén et al. [2008](#)) or reported such trade-off using gait parameters lacking of functional significance (Verrel et al. [2009](#)).

Accordingly, the objective of the present study was to test the likelihood of the dual-process account (external focus/resource competition) relating cognitive control demand and gait variability and determine whether the negative effects of attentional resource competition on gait variability become more pronounced as we get older. Cognitive control is often invoked by environmental stimuli that are perceptually salient or that trigger default action tendencies (Braver and Cohen [2000](#); Braver et al. [2002](#); Miller and Cohen [2001](#)). The classic and probably most widely known example of a stimulus situation that imposes cognitive control is the Stroop task (Stroop [1935](#)) with the presentation of color words written in a conflicting ink (e.g., the word “red” written in a

blue ink). In the ink color naming condition, a default action tendency is to respond with the color word even when the instruction is to respond with the ink color. This phenomenon, called the “Stroop effect,” has thus a “built-in” perceptual bias since the semantic information is perceptually more salient than the non-semantic one. Thought, a limitation in the classical approach to cognitive control is that the conflict is either present (i.e., “read the ink color”) or absent (i.e., “read the color word”). Hence, a fine-grained analysis of age-related differences in cognitive control would not be possible. To address this issue, Hugdahl et al. (2009) proposed a dichotic listening task allowing a parametric manipulation of the degree of cognitive conflict and a corresponding quantification of the degree of cognitive control needed to resolve the conflicting information. Literally, dichotic listening means that two different auditory stimuli (i.e., simple speech sounds like consonant-vowel syllables) are presented, one to the right ear and one to the left ear, at the same time (Bryden 1988; Hugdahl 2003; Tervaniemi and Hugdahl 2003). In a non-forced (NF), free recall, condition (i.e., participants report the syllable they hear best with no instruction on focus of attention), a preference for the syllables given to the right ear over those given to the left ear is normally found in healthy adults. There are at least three explanations for this ear bias. The structural hypothesis suggests that the right ear projects more strongly to the language dominant left hemisphere (Kimura 1961). The callosal relay hypothesis is based on the influence of inhibitory connections via the corpus callosum (Asbjørnsen and Hugdahl 1995). The attentional hypothesis suggests that each hemisphere primarily directs attention to contralateral space and because the left hemisphere is dominant for processing speech stimuli, attention is primarily directed to the right ear (Kinsbourne, 1970, 1975). However, by instructing participants to attend exclusively to one ear [forced-right (FR) or forced-left (FL)], the right ear advantage (REA) can be modulated, that is, top-down (instruction-driven) attentional modulation of the bottom-up (stimulus-driven) lateralized perceptual REA effect is obtained. Typically, the REA is increased in the FR condition, and decreased, or switched to a left ear advantage (LEA), in the FL condition (Bryden et al. 1983; Hugdahl and Andersson 1986). Hence, humans have the ability to overcome a default, stimulus-driven, REA by switching attention from one ear to the other. This can be seen as a rough, experimental, analogue to the well-known “cocktail party phenomenon,” which also involves the use of attention in switching between multiple speech inputs (Cherry 1953).

Besides its ecological validity, the strength of the dichotic listening task is twofold in the context of the dual-process account of cognitive-motor interactions (Huxhold et al. 2006; Lövdén et al. 2008; Schaefer et al. 2015; Verrel et al. 2009). First, the cognitive demand and effort parametrically increase from the NF to the FL condition (Hugdahl et al. 2009). In the NF condition, attention is attracted in a non-volitional way (i.e., bottom-up) to the right ear. Inversely, attentional processing becomes volitional (i.e., top-down) in the FR and FL conditions, leading to further cognitive effort compared with the NF condition. Moreover, greater volitional, or intentional, control is required in FL due to antagonistic actions of the top-down and bottom-up processes, with the bottom-up process pushing for a right ear response and the top-down process pushing for a left ear response. This is in contrast to the FR condition where the two processes act synergistically, both pushing for a right ear response. To summarize, although the auditory stimuli are

identical across conditions, the three different instructional conditions allow teasing apart a lateralized perceptual process (NF condition), an orienting process with synergistic bottom-up and top-down effects (FR condition), and a cognitive control process with a conflicting top-down effect that needs to override the bottom-up, automatic response. The NF condition in this context serves as a baseline condition to evaluate the effects in the FR and FL conditions (Hugdahl et al. [2009](#)). Second, inhibitory control is involved in the two forced attention conditions to prevent the irrelevant stimulus from gaining access to the focus of attention, with increasing requirement for that control from FR to FL (Della Penna et al. [2007](#); Hugdahl et al. [2009](#)). Functional magnetic resonance imaging (fMRI) studies have confirmed additional recruitment of cognitive control to resolve the interference in the FL condition as compared to the FR condition, showing remaining significant activations in the frontal and anterior cingulate cortex, when contrasting fMRI images obtained during the FL condition with those obtained during the FR condition (Thomsen et al. [2004](#); see also Hugdahl et al. [2009](#) and references therein). Considering that cognitive control requires intact frontal lobes, and particularly the dorsolateral and ventral parts of the prefrontal cortex (Braver et al. [2002](#)), as well as the dorsal part of the anterior cingulate (Bush et al. [2000](#)), it has been argued that the FR and FL conditions differ in the degree to which they involve cognitive control and specifically inhibitory control. Given that inhibitory processes play an important role in balance control, especially in older adults (Redfern et al. [2001](#), [2009](#)), dichotic listening is likely to promote attentional resource competition with gait. As regards to walking, our analysis focused on step-to-step variability, including spatial (step length and step width variability) and temporal (step time variability) variability parameters. Increments in these parameters have been consistently associated with both impaired gait control and higher risk of falls among older adults (Hausdorff et al. [2001](#); Brach et al. [2005](#); Verghese et al. [2009](#)), as well as increased reliance on attention and cognitive control (Hausdorff [2005](#)).

On the basis of the dual-process account relating cognitive control to gait variability (Lövdén et al. [2008](#)), we hypothesized: (i) no dual-task-related changes (i.e., recall accuracy and modulation of the ear advantage, assessed by the number of errors and the laterality index, respectively) in dichotic listening performance; (ii) a decreased variability of step width, step time, and step length in the NF condition (external focus of attention) and an increasing variability from the NF through the FR to the FL condition (resource competition); and (iii) further increases in step parameter variability from the NF through the FR to the FL condition (larger resource competition) in older adults due to more limited attentional resources with aging.

Methods

Study population

Young adults ($n = 20$) aged between 20 and 35 years and older adults ($n = 19$) aged 65 years or older were recruited for the experiment. The two samples matched regarding their demographic characteristics (Table [1](#)). Inclusion criteria were (1) native English speakers; (2) right-handed (Edinburgh Handedness Inventory; Oldfield [1971](#); see also Foundas et al. [2006](#), who demonstrated that, in verbal dichotic listening, right-

and left-handers differ in the size of the shift in laterality when attention is directed to either the right or left ear); (3) living independently in the community; (4) able to ambulate without the use of, or assistance from, a prosthetic device, a fixed or mobile walking frame, or other assistive devices (e.g., brace, cane, crutch) or without the assistance of another person; and (5) not diagnosed with neurologic conditions (e.g., Alzheimer’s disease, Parkinson’s disease, stroke, and multiple sclerosis) or other conditions (e.g., dementia, moderate or severe chronic obstructive pulmonary disease, weight-bearing pain, chest pain at rest or during activity, previous history of myocardial infarction, dyspnea at rest, or use of supplemental oxygen). Exclusion criteria were (1) a hearing level too poor to perceive speech (i.e., a threshold higher than 20 dB at 2 kHz) and (2) inter-aural, pure-tone threshold difference exceeding an average of 10 dB in the speech range during audiometric evaluation (hearing differences of 10 dB between ears are found to affect dichotic listening performance, Asbjørnsen et al. 2000). Thus, all participants underwent an audiometric test performed for each ear at .25, .5, 1, 2, 4, and 8 kHz, with testing repeated at 1 kHz. Informed consent was obtained from all participants prior to data collection according to the guidelines of the university’s institutional review board.

Protocol overview

The experiment took place in the Nebraska Biomechanics Core Facility (Omaha, NE). It consisted of a sitting session and a walking session, counterbalanced between participants. In the sitting session, the participants underwent neuropsychological testing. Then, they performed the dichotic listening task while seated in order to establish baseline cognitive performance. In the walking session, they walked on a treadmill at their preferred walking speed (Table 1), either without an explicit attentional requirement (i.e., control walking condition) or while performing the three conditions (NF, FR, and FL) of the dichotic listening task (i.e., dual-task conditions). Each session lasted 1 h and 30 min, with a 1-week interval between sessions.

Table 1 Baseline characteristics of the adult participants

| | | Young | | Older | | Statistics |
|-----------------|--------------------------|--------------|------------|--------------|-------------|-------------------------------------|
| Demographics | Gender (M/F) | 8/12 | | 10/9 | | $\chi^2 (1, N = 39) = .63; p = .43$ |
| | Age (years) | 24.45 (.87) | [20–35] | 69.26 (1.11) | [65–79] | $t(37) = -31.96; p < .0001$ |
| | Height (m) | 1.73 (.02) | [1.6–1.86] | 1.71 (.02) | [1.57–1.91] | $t(37) = 1.05; p = .29$ |
| | Body mass (kg) | 70.41 (2.63) | [52–94] | 77.45 (2.78) | [59–105] | $t(37) = -1.83; p = .07$ |
| | Education (years) | 16.5 (.43) | [11–20] | 17.63 (.82) | [13–24] | $t(37) = -1.22; p = .23$ |
| Cognition | DS forward | 11.78 (.61) | [7–16] | 10.05 (.48) | [7–14] | $t(37) = 1.79; p = .08$ |
| | DS backward | 7.6 (.47) | [4–13] | 6.47 (.56) | [2–11] | $t(37) = 1.89; p = .06$ |
| | DS total | 19.47 (.94) | [12–29] | 16.52 (.93) | [10–23] | $t(37) = 1.96; p = .04$ |
| | MMSE | 29 (.21) | [27–30] | 28.94 (.32) | [26–30] | $t(37) = .13; p = .9$ |
| Depression | GDS | | | 1.21 (.32) | [0–4] | |
| Fear of falling | MFES | | | 9.94 (.04) | [9–10] | |
| Gait | PWS (m s ⁻¹) | 1.06 (.03) | [.72–1.43] | .77 (.04) | [.45–1.02] | $t(37) = 4.81; p < .0001$ |

Entries are mean (standard error) [range]

DS digit span, MMSE Mini-Mental State Examination, GDS Geriatric Depression Scale, MFES Modified Falls Efficacy Scale, PWS preferred walking speed

Neuropsychological test battery

The participants first underwent tests of general cognitive functioning, involving the Mini-Mental State Examination (see Folstein et al. [1975](#) for normative scores) and the Wechsler Adult Intelligence Scale—Third Edition (WAIS-III) forward and backward digit span tests (Wechsler [1981](#); see Monaco et al. [2013](#) for normative scores). Further, baseline data with respect to the number of falls in the year prior to the experiment, fear of falling (Modified Falls Efficacy Scale; Hill et al. [1996](#)), and depression (15-item Geriatric Depression Scale; Sheikh and Yesavages [1986](#)) were obtained for the older adults.

Dichotic listening task

The auditory stimuli in the English version of the standard Bergen dichotic listening paradigm (Hugdahl and Andersson [1986](#); Hugdahl [2003](#)) were phonetically meaningful but semantically meaningless consonant-vowel (CV) syllables (/ba/, /da/, /ga/, /pa/, /ta/, /ka/). The six CV syllables were combined in pairs in all possible combinations, thus forming a total of 36 possible dichotic pairs, including the 6 homonymic pairs (da-da, etc.). The homonymic pairs were used as a perceptual control to ensure that participants were able to perceive the different CV syllable stimuli (i.e., three out of six were considered adequate); however, they were not included in the statistical analysis. Thus, the maximum score was 30 for each ear. In each trial, one CV syllable was presented to the left ear and another simultaneously to the right ear. Each CV syllable was originally read by a male voice with intonation and intensity held constant. Each CV syllable pair was recorded three times, with three different randomizations of the 36 dichotic pairs. Thus, the total number of trials was 108. The 108 trials were divided into three blocks of 36 trials, one block for each instructional condition (NF, FR, and FL). Each CV syllable stimulus was approximately 480–550 ms in duration, and the inter-stimulus interval was approximately 4000 ms. The total duration of each condition was set at 3 min.

A standard PC running the E-prime programming platform (www.pstnet.com; Psychology Software Tools) was used for stimulus presentation and response collection. Oral responses were also recorded using a digital voice recorder as back-up and analyzed further. Before the dichotic listening task was performed, the participants were shown the six syllables written in large font on a piece of paper placed in front of them and were asked to name them. This was done to ensure that the participants were familiar with the syllables and their correct pronunciation. The stimuli were presented via noise-cancelling headphones. The audio output from the computer was monitored by the experimenter through an extra set of headphones placed only over one ear in order to follow the progress of the test.

The test administration and scoring procedure were the same as those of Hugdahl and Andersson ([1986](#)). The dichotic listening task was divided into three different conditions, which differed with regard to the instruction on how to focus attention. In all three

conditions, the participants were told that they would be presented with a list of CV syllables and that their task was to answer with the syllable they heard on each trial. Before the actual testing, a few practice trials were presented, and the participants were instructed to report whether they heard the CV syllables and to give feedback about whether the audio level was loud enough. In the NF condition, participants were told to report after each trial the single CV syllable which they heard best or most clearly from the six possible syllables. In the FR and FL conditions, they were asked to listen to and report the syllables from the right or left ear, respectively, and to ignore any sounds they might hear in the other ear. In order to make sure that the participant had understood which ear to attend to during the FR and the FL conditions, the experimenter touched or pointed the ear of the participant on that side. The NF condition was always presented first to avoid that prior execution of either of the forced conditions produced carryover effects, with the risk of biasing attention toward the previously attended ear. The presentation order of the two forced conditions was counterbalanced across participants (either FR before FL or FL before FR).

Gait task

Prior to data collection, reflective markers were attached to a tight-fitting suit at specific anatomical landmarks of each participant's lower limbs (Nigg et al. [1993](#); Vaughan et al. [1999](#)). The anatomical landmarks were the anterior and posterior superior iliac spine, lumbosacral joint, greater trochanter of the femur, lateral mid-thigh, front lower thigh, lateral and medial epicondyles of the femur, front mid-shank, lateral lower shank, lateral and medial malleoli, lateral border of the fifth metatarsal head, medial border of the first metatarsal head, lateral and medial processes of the calcaneal tuberosity, heel, and between the second and third metatarsophalangeal joints. The three-dimensional positions of the markers were collected at 100 Hz with a Motion Analysis Eagle Digital system (eight cameras), which was interfaced with the EVaRT software (version 5.0, Motion Analysis Corporation, Santa Rosa, CA).

All participants were fitted into the LiteGait® (Mobility Research, LLC, Tempe, AZ) harness system for safety. The LiteGait® supported the participants only if balance was lost during testing. Participants were given ample time to familiarize themselves with walking on the treadmill prior to testing. The preferred walking speed (PWS) was established using a well-established protocol (Jordan et al. [2007](#)). Initially, the participants walked at a relatively slow speed, and then the investigator increased the speed in $.1 \text{ km h}^{-1}$ increments until the participants reported their PWS. The speed was then increased by approximately 1.5 km h^{-1} and then decreased by $.1 \text{ km h}^{-1}$ until the PWS was re-established. This procedure was repeated until a close match was achieved (less than $.4 \text{ km h}^{-1}$ difference). While establishing their PWS, participants were prevented from viewing the treadmill speed display. Afterwards, participants walked either without an explicit attentional requirement (i.e., control walking condition) or while performing the three conditions (NF, FR, and FL) of the dichotic listening task (i.e., dual-task conditions). No specific instructions were given about task prioritization under dual-task conditions. For each condition, participants walked for 3 min and ample rest was provided between conditions. The duration of 3 min was chosen as it is difficult

to maximize concentration or sustained attention for a longer period of time (Hunt and Lansman, [1986](#); Aylward et al. [1997](#); Griggs et al. [1998](#)). The order of the walking conditions was counterbalanced between participants.

Assessment of dichotic listening performance

A response was counted as correct when the recalled syllable matched the syllable presented to either the right (RE) or left (LE) ear on each trial; if the response did not match either syllable, or no response was given, it was counted as an error. The number of errors (Err) was calculated as follows:

$$\text{Err} = 30 - (\text{RE} + \text{LE})$$

The laterality index (LI) was calculated to quantify the ear advantage using this formula:

$$\text{LI} = \left[\frac{\text{RE} - \text{LE}}{\text{RE} + \text{LE}} \right] \times 100$$

The laterality index thus ranged between +100 % (maximum REA) and -100 % (maximum LEA). Values close to 0 % indicate no ear advantage. In the NF condition, a 10 % LI is within the normal range found in healthy right-handers (Hugdahl [2003](#)). Attention clearly modulates the direction and degree of ear asymmetry in dichotic listening. A reduction in the ability to modulate the ear advantage is typically observed with advancing age when instructed to focus attention on and report the left ear syllables. As a matter of fact, older adults fail to report more syllables from the left ear during the FL condition (Hugdahl et al. [2009](#)). This may be attributed to a breakdown of the executive attention network, which is mediated by frontal (inhibitory control of attention) and parietal (spatial selective attention and “disengagement processes” to switch attention from one ear to the other) regions. It has been suggested that interhemispheric (collosal atrophy) as well as intrahemispheric (subcortical white matter lesions) disconnectivity contributes to an age-related increased difficulty focusing attention on the left ear (Bouma and Gootjes [2011](#)).

Assessment of step variability

The marker trajectories were low-pass filtered at 10 Hz with a zero-lag Butterworth filter. Step length and step time calculation required first identifying toe-off events from the maximum backward displacements of the (antero-posterior) x-coordinates of the toe markers (i.e., right and left markers located between the second and third metatarsal phalangeal joints). Step length was afterwards determined as the horizontal distance between the positions of the toe markers at each toe-off event, and step time was obtained as the time interval between consecutive toe-off events (Decker et al. [2012](#), [2013](#)). Step width required first calculating the right and left foot midpoints. The foot midpoint was defined as the midpoint of the vector connecting the heel marker to the toe marker. Step width was afterwards determined as the medio-lateral distance between the foot midpoints calculated over consecutive foot-flat instants. Specifically, the right (or left) foot-flat instants were identified when the left (or right) swing limb's

knee passed in front of the right (or left) stance limb's knee, using the (antero-posterior) x-coordinates of the markers located on the lateral epicondyles of the femurs. For consistency across subjects, step time, step length, and step width time series were shortened to 256 data points, which was the number of consecutive steps collected from the slowest subject. All step parameters were calculated using MATLAB (The MathWorks, Inc., MA, version 7.0).

Step-to-step variability was afterwards determined from the standard deviation of the time series instead of the coefficient of variation following previous recommendations (Lövdén et al. [2008](#)). First, the need for normalizing to the mean was not necessary given that our central hypothesis focused on an age \times cognitive demand interaction effect (i.e., looking for a greater increase in step parameter variability with cognitive demand in older adults compared to their younger counterparts) rather than on a main effect of age. Second, normalizing the standard deviation with the mean would have been meaningful in case an age \times cognitive demand interaction effect also applies for the estimates of the mean step parameters, which was neither predicted nor empirically found. Accordingly, we stayed closer to the raw data and avoided relying on the normalization assumptions involved when computing the coefficient of variation (e.g., mean has priority over variability).

Statistical analysis

The gait (standard deviations of step length, step time, and step width) and cognitive-dichotic listening (laterality index, number of errors) dependent variables displayed acceptable normal distribution as assessed using the Kolmogorov-Smirnov test. The gait variables were examined using two separate mixed-design analyses of variance (ANOVAs). A 2 (group: young adults, older adults) \times 2 (condition: walking, walking + NF) ANOVA addressed the effect of the low level of attentional demand on step variability. A 2 (group: young adults, older adults) \times 3 (condition: walking + NF, walking + FR, walking + FL) ANOVA addressed the effect of increasing attentional demand on step variability. Given that slower speeds in the older adults may confound the effect of age on step variability (e.g., Kang and Dingwell [2008](#)), we also adjusted the step variability dependent variables by the group means of the PWS, thereby running analyses of covariance (ANCOVAs) with PWS as the covariate (see for instance Cignetti et al. [2012](#) for a similar approach). For dichotic listening performance, we performed a 2 (group: young adults, older adults) \times 2 (session: sitting, walking) \times 3 (condition: NF, FR, FL) ANOVA. When the assumption of sphericity was violated for the within-subject effect (as evaluated using Mauchly's test), the degrees of freedom (reported truncated to the nearest integers) and thereby the F value were corrected using the Greenhouse-Geisser correction in all above analyses. Post hoc multiple comparisons were conducted using the Newman-Keuls test. Effect sizes are reported as partial eta-squared (η^2). Statistical significance was set at .05. Statistica (version 10, Statsoft, Inc., Tulsa, OK, USA) was used to perform all analyses.

Results

Baseline characteristics of the young and older adults

All participants scored more than 25 on the MMSE and more than 6 and 5 on the WAIS-III forward and backward digit span tasks, respectively, which reflected preserved general cognitive function (Table 1). Moreover, the older adults reported no falls in the year prior to the experiment, had no fear of falling (i.e., MFES scores close to 10), and had an average score very close to 1 on the 15-item GDS, indicating no symptoms of depression.

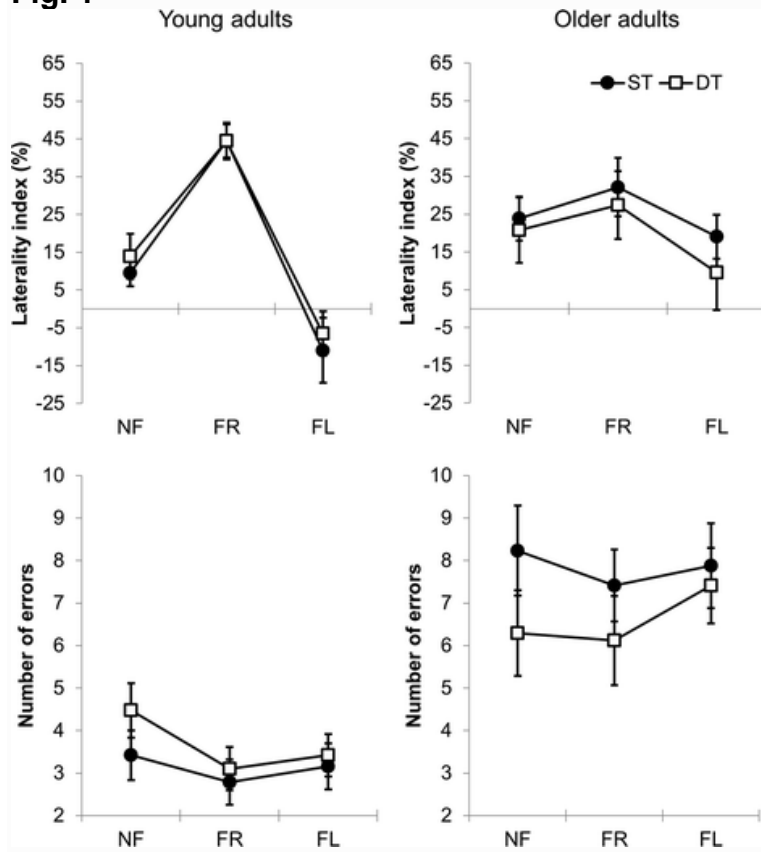
Dichotic listening performance

Mixed-design ANOVA conducted on the laterality index revealed a significant *condition* main effect ($F[1, 45] = 26.72, p < .001, \eta^2 = .39$) and a *group* \times *condition* interaction effect ($F[1, 45] = 8.30, p = .003, \eta^2 = .12$). In young adults, the laterality index significantly increased from the NF to FR conditions and significantly decreased from the FR to FL conditions, reaching negative values in the latter condition (Fig. 1). As expected, young adults showed REA in NF, increased REA in FR, and LEA in FL. The trend was less pronounced in older adults, which explained the interaction effect. Post hoc tests did not reveal any significant differences between the three conditions, meaning that older adults failed to modulate the REA. With respect to the number of errors, there was a significant *group* main effect ($F[1, 34] = 22.77, p < .001, \eta^2 = .41$), with significantly larger values in older adults as compared to young adults (Fig. 1). Finally, the mixed-design ANOVA conducted on the number of errors revealed a *group* \times *session* interaction effect ($F[1, 34] = 4.76, p = .036, \eta^2 = .12$). This effect was explained by the fact that young adults made more errors, whereas older adults made fewer errors while walking than while seated.

Step variability

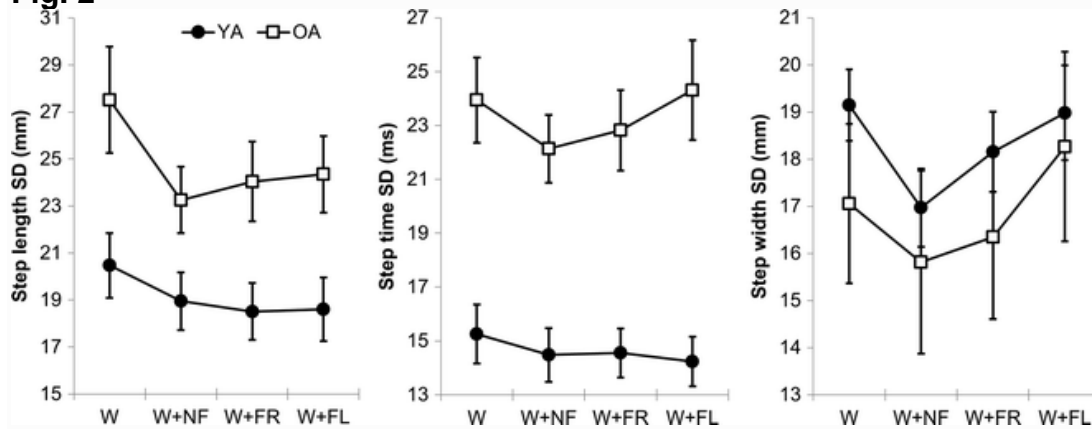
ANOVAs that evaluated the effect of the lowest level of attentional demand in dichotic listening (NF condition) on step variability revealed a significant *group* main effect for step length ($F[1, 37] = 7.07, p = .01, \eta^2 = .16$) and step time ($F[1, 37] = 22.51, p < 10^{-5}, \eta^2 = .38$), with a lower variability (i.e., lower standard deviation values) in the young adults than in the older adults (Fig. 2). There was also a significant *condition* main effect for the variability of step length ($F[1, 37] = 12.98, p < .001, \eta^2 = .26$), step time ($F[1, 37] = 7.33, p = .01, \eta^2 = .16$), and step width ($F[1, 37] = 6.39, p = .01, \eta^2 = .15$). For all condition effects, post hoc analyses showed decreased variability in the walking + NF condition as compared to the control walking condition. ANCOVAs run (with PWS as the covariate) on step variability dependent variables only partially confirmed the above results. There remained a significant decreased variability in step length ($F[1, 37] = 7.85, p < .001, \eta^2 = .18$) and step width ($F[1, 37] = 6.39, p = .01, \eta^2 = .15$) and a marginally significant decrease in step time variability ($F[1, 37] = 3.07, p < .01, \eta^2 = .08$) from the walking condition to the walking + NF condition (i.e., *condition* main effect), while the *group* main effects for step length, step time, and step width variability were no longer significant. Therefore, increased variability in older adults resulted from slower walking speeds.

Fig. 1



Mean (standard error) dichotic listening performance as evaluated from the laterality index and the number of errors. For both young and older adults, performance is reported as a function of dichotic listening condition (*NF* non-forced, *FR* forced-right, *FL* forced-left) and session (*ST* single-task, *DT* dual-task)

Fig. 2



Changes in mean (standard error) values of step length, step time, and step width variability with age group and condition. Age group includes young adults (YA) and older adults (OA). Condition includes walking alone (*W*) and walking while performing dichotic listening in non-forced (*W + NF*), forced-right (*W + FR*), and forced-left (*W + FL*)

ANOVAs that addressed the effect of increasing attentional demand in dichotic listening on variability yielded a significant *group* main effect for step length ($F[1, 37] = 7.54, p < .01, \eta^2 = .17$) and step time ($F[1, 37] = 18.91, p < .001, \eta^2 = .34$), with a

lower variability in the young adults than in the older adults (Fig. 2). The analyses also revealed a significant *condition* main effect for step time variability ($F[2, 69] = 3.43, p = .04, \eta^2 = .1$) and step width variability ($F[2, 68] = 5.52, p = .006, \eta^2 = .13$), whose values were larger in the walking + FL condition than in the walking + NF condition. Inspection of the data (Fig. 2) showed that such increasing trend from walking + NF condition to walking + FL condition applied to both young and older adults with regards to step width variability, while it was mainly driven by the older adults regarding step time variability. Although the *group* \times *condition* interaction was not found to be significant for step time variability, one-way repeated measures ANOVAs run separately on the young adult and the older adult group data confirmed our intuition, with a significant increase of step time variability in the older adults only ($F[2, 36] = 3.32, p = .04, \eta^2 = .15$). Finally, the *group* main effect for step length and step time variability disappeared using ANCOVAs (i.e., the greater variability in the older adults resulted from their slower speeds), while the *condition* main effect for step time variability ($F[2, 69] = 3.23, p = .04, \eta^2 = .07$) and step width variability ($F[2, 68] = 5.52, p = .006, \eta^2 = .13$) remained significant.

Discussion

The present experiment examined age-related changes in the relationship between gait control, as evaluated by step-to-step variability, and the difficulty of a cognitive task involving inhibitory control. The results are twofold. First, a U-shaped relationship was observed in young and older adults with respect to step width variability, with a reduced variability in the NF condition and an increasing variability from the NF to the FL conditions. Second, step time variability was also related to attentional demand in a U-shaped manner in the older adults, with the turning point at NF, while step length variability decreased in NF but leveled out for higher attentional demands. Inversely, variability in both step time and step length was not modulated by attentional demand in the young adults. Therefore, a U-shaped relationship was observed for variability in both step width and step time in the older adults and for step width variability only in the young adults, supporting a dual-process account relating cognitive demand and gait control in both groups. Low attentional demand (NF condition) improved gait control (i.e., decreased variability), likely shifting the focus of overt attention away from the walking task. Higher demands (forced attention conditions) overshadowed this beneficial effect, hindering gait control (i.e., increased variability) through attentional resource competition. However, although these findings support the dual-process account (Lövdén et al. 2008; Verrel et al. 2009), the fact that step variability in the most cognitively demanding FL condition did not exceed that in the control walking condition is counterintuitive in the framework of attentional resource competition. An explanation may be that walking alone already required attentional resources to not walk off the treadmill, the person regulating his/her gait by limiting deviations from a “preferred operating point” (Dingwell et al. 2010; Decker et al. 2012; Dingwell and Cusumano 2015). Because of this control strategy and given that treadmill walking imposes boundaries on the extent of deviations from one step to the next, exceeding a ceiling value (both in the antero-posterior and medio-lateral directions) might have not been possible in the FL condition. Another explanation may have to do with a too low degree of interference between cognitive processing in the FL condition and gait

control. However, this is unlikely given that the degree of cognitive demand is considered to be high in that condition (Hugdahl et al. [2009](#)). Moreover, the demand in the FL condition is on inhibitory control, which is also largely involved during walking through sensory integration processes for balance control (Redfern et al. [2001](#), [2009](#)).

Previous investigators suggested that step time and step width variability are associated with different components of walking, namely rhythmic stepping pattern (i.e., progression) and balance control (i.e., walking stability), respectively (Gabell and Nayak [1984](#); Brach et al. [2005](#); Hausdorff [2005](#); Montero-Odasso et al. [2011](#)). In this framework, our results suggested that consuming attentional resources with dichotic listening affected balance control similarly in both young and older adults, whereas it also altered control of rhythmic stepping pattern in the older adults. Therefore, the effect of aging seems to be expressed through a dual-task cost that extends from the balance-related gait characteristic to the stepping-related gait characteristic. This effect is likely a direct consequence of the declined attentional reserve capacity that occurs with advancing age (Lindenberger and Baltes [1994](#)), which increases competition for attention resources between gait and the secondary cognitive task. However, the absence of a further increase in step width variability as a function of the attentional demand in the older adults is a bit surprising from the reserve capacity perspective. A possible explanation for this null finding may be that a more pronounced increase in step width variability could have led to incident mobility (e.g., falls) in the older adults, excessive step width variability having previously been found to be associated with a fall history (Brach et al. [2005](#)). Alternatively, the older adults included in the study were healthy, which may have lessened the effects of attentional resource competition on balance control during gait. Examining gait-related dual-task effects in vulnerable older adults, such as individuals with a frailty phenotype or at risk of falling, using a protocol similar to the present study, may help address these issues.

With respect to cognitive performance, the older adults performed worse than the young adults on dichotic listening both in single-task and dual-task conditions. First, the older adults made more errors than their younger counterparts. Second, although both groups showed a REA in the NF condition, only the young adults were able to magnify and tone down this advantage in the FR and FL conditions, respectively. Overall, these results suggest a reduced capacity for cognitive control in older adults, which is consistent with previous studies (Andersson et al. [2008](#); Redfern et al. [2009](#)). On the other hand, we found an unexpected result regarding the number of errors. The young adults made more errors while walking than while seated, indicating a dual-task cost in the cognitive domain. Inversely, there was a dual-task gain in the older adults with fewer errors while walking. Some previous studies already showed increased cognitive performance when walking was performed simultaneously with a concurrent cognitive task (Decker et al. [2012](#); Schaefer et al. [2010](#); Verrel et al. [2009](#)). This effect was interpreted in terms of a general increase in arousal induced by physical activity. Similarly, walking may have boosted arousal in the older adults and positively affected their dichotic listening performance. That being said, the dual-task related changes in cognitive performance in young and older adults should not be over-interpreted. Indeed, the laterality index, which is a very common indicator of dichotic listening performance (Hugdahl et

al. 2009), was not affected by the dual task. Accordingly, a cautious conclusion is that performance on the cognitive task was rather preserved under dual-task conditions in both groups.

The fact that the cognitive performance remained practically equivalent under both single- and dual-task conditions is important with respect to the task prioritization strategy used by the subjects. Indeed, a decreased gait control (i.e., increased step variability) combined with a preserved cognitive performance under dual-task conditions reflects a “posture second” strategy, where the cognitive task, and thus the attentional resources allocated to it, is prioritized over the gait task (Bloem et al. 2006; Yogev-Seligmann et al. 2012a, b). Accordingly, our data are in favor of such a strategy in both groups, providing further support to the idea that healthy adults, young and older, do not use “posture first” as a default strategy (Yogev-Seligmann et al. 2010, 2012b). The “posture second” strategy could be due to either an impaired judgment of the individuals with respect to the risk of their actions, exposing themselves to the risk of falling, as in patients with neurodegenerative diseases characterized by a cognitive decline (Bloem et al. 2006), or a high postural reserve that enables the individuals to focus on the cognitive task even when the gait threat is high (Bloem et al. 2006; Yogev-Seligmann et al. 2010, 2012a, b; Holtzer et al. 2014). Given that our subjects were cognitively intact, we propose that a high postural reserve was responsible for the “posture second” strategy they used. In fact, the gait task was fairly easy (i.e., at preferred walking speed), our subjects did not feel sufficiently threatened regarding balance and gait control to be in need of a “posture first” strategy. If the gait task was a little closer to their postural reserve capacity, they might have preferred to attend more their gait. The important point here is that the preference in preserving the cognitive task over gait control undoubtedly magnified the effects of attentional resource competition on gait with increasing cognitive task difficulty (i.e., the rising part of the U-shaped relationship). Indeed, a posture first strategy could have prevented observation of gait control decrements due to attentional resource competition (increased type II error, Verghese et al. 2007). Therefore, interpreting dual-task performance within the reserve capacity view should be systematically carried out in relation with the prioritization strategy used by the subjects.

This study is limited by the moderate sample size and the relative homogeneity of the older adults, all presenting a good functional status. Accordingly, some findings, such as the absence of further decrements in balance control when increasing the attentional demand and the prioritization of the cognitive task over the gait task, may not be generalizable to all community-dwelling older adults. Therefore, reproduction of the present findings in a larger sample, including also older persons with lower functionality, is warranted. Furthermore, we used treadmill walking instead of overground walking to produce robust estimates of step variability. The corollary is that treadmill walking has been found to be associated with a reduction of variability (Dingwell et al. 2001), which may have masked some dual-task related gait changes as previously mentioned.

In conclusion, our study provided evidence for a U-shaped relationship between cognitive demand and step variability, presumably indicating a trade-off between an

external focus of attention and a competition for attentional resources. Thus, it appears appropriate to interpret the dual-task walking findings from young adulthood to old age using this dual-process model framework. Furthermore, the fact that the generalizability of the model to step parameters was not only related to balance control (step width variability) but also to rhythmic stepping pattern (step time variability) in older adults reveals that attentional resources become involved in all facets of walking with aging. Finally, our findings suggest that prioritizing the cognitive task over the gait task (i.e., a posture second strategy) may constitute the default strategy used by healthy individuals in dual-task walking. Strategies of task prioritization are also important to consider when interpreting the effects of dual tasking on gait.

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