Journal of Clinical and Experimental Neuropsychology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ncen20

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To cite this article: Marta Maria Gorecka , Olena Vasylenko & Claudia Rodríguez-Aranda (2020): Dichotic listening while walking: A dual-task paradigm examining gait asymmetries in healthy older and younger adults, Journal of Clinical and Experimental Neuropsychology, DOI: 10.1080/13803395.2020.1811207

To link to this article: https://doi.org/10.1080/13803395.2020.1811207

JOURNAL OF CLINICAL AND EXPERIMENTAL NEUROPSYCHOLOGY
https://doi.org/10.1080/13803395.2020.1811207

Dichotic listening while walking: A dual-task paradigm examining gait asymmetries in healthy older and younger adults

Marta Maria Gorecka, Olena Vasylenko and Claudia Rodríguez-Aranda

Department of Psychology, UiT- the Arctic University of Norway, Tromsø, Norway

ABSTRACT

Dual-task studies have employed various cognitive tasks to evaluate the relationship between gait and cognition. Most of these tests are not specific to a single cognitive ability or sensory modality and have limited ecological validity. In this study, we employed a dual-task paradigm using Dichotic Listening (DL) as concomitant cognitive task to walking. We argue that DL is a robust task to unravel the gait-cognition link in different healthy populations of different age groups. Thirty-six healthy older adults (*Mean* = 67.11) and forty younger adults (*Mean* = 22.75) participated in the study. DL consists of three conditions where spontaneous attention and attention directed to right or left-ear are tested while walking. We calculated dual-task costs (DTCs) and percent of baseline values for three spatio-temporal gait parameters as compared to single-walking during three DL conditions. Results showed that both groups had larger DTCs on gait during volitional control of attention, i.e., directing attention to one specific ear. Group differences were present across all DL conditions where older adults reported consistently less correct stimuli than younger participants. Similar findings were observed in the neuropsychological battery where older participants showed restricted abilities for executive functioning and processing speed. However, the main finding of this investigation was that younger adults exhibited unique adjustments in step length variability as shown by changes in DTCs and percent of baseline values. Particularly, an asymmetric effect was observed on the young group when attending right-ear stimuli. We interpreted this gait asymmetry as a compensatory outcome in the younger participants due to their optimal perceptual and motor abilities, which allow them to cope suitably with the dual-task situation. Many studies suggest that gait asymmetries are indicators of pathology, the present data demonstrate that gait asymmetries arise under specific constraints in healthy people as an adaptation to task requirements.

ARTICLE HISTORY
Received 27 April 2020
Accepted 7 August 2020

KEYWORDS
Dual-task; dichotic listening; healthy aging; walking over-ground; asymmetry

Introduction

Aging is associated with changes in cognition and motor functions. Specifically, these changes affect gait in older adults (Montero-Odasso et al., 2012; Morris et al., 2016). In order to address the interrelation between walking and cognition, a classical method known as dual-task paradigm has been employed. Dual-task experiments require subjects to perform two tasks simultaneously in order to measure the influence of a primary task on a secondary task. Thus, the dual-task paradigm is utilized in gait studies by simply asking individuals to walk while they perform in parallel a cognitive task (Pashler, 1994). A challenge in this line of research is the fact that numerous cognitive tasks have been used as concurrent tasks in dual-tasking and these are either not specific to one cognitive function or too intricate that findings cannot be generalized to everyday situations (for review Beauchet et al., 2005; Boisgontier et al., 2013; Patel et al., 2014).

Al-Yahya et al. (2011) showed that the cognitive tasks most recurrently employed to challenge gait were those requiring mental tracking. However, mental tracking tasks exist in various sensorial modalities and in a diversity of type of tasks that it becomes challenging to unravel how specific cognitive demands affect specific gait parameters (Shumway-Cook et al., 1997). For this reason, our group has applied a Dichotic Listening (DL) task, which is a robust test for the assessment of central auditory language processing, laterality, and interhemispheric interactions as well as divided and sustained attention.

DL and aging effects

In general, DL tasks consist in applying different stimuli (e.g., words, numbers, or syllables) to each ear at the same time (Bryden, 1988). One dichotic listening approach widely employed is the Bergen Dichotic Listening Task (Hugdahl & Andersson, 1986), which we have selected. In

CONTACT Marta Maria Gorecka, marta.m.gorecka@uit.no Department of Psychology, UiT- the Arctic University of Norway, Tromsø, Norway
Supplemental data for this article can be accessed here.

this task, different consonant-vowel syllables are presented simultaneously to each ear in three conditions. In the first condition (Non-Forced, NF) participants report freely the stimuli that seem most salient. Then, in the other two conditions subjects are asked to either report stimuli from right or left-ear while inhibiting stimuli from the opposite ear (Forced Right/Left, FR/FL). Due to the decussation of the auditory pathways, right-handed persons report more likely responses from the right ear and such a phenomenon is known as the "Right Ear Advantage" (REA), which reflects a dominant left-hemisphere processing for language (Asbjørnsen & Hugdahl, 1995; Bryden, 1988; Kimura, 1967). This peculiarity in right-handed individuals causes that attending to the left side becomes more demanding. Thus, the increment in cognitive demands in DL, from NF to the FR and FL condition, makes possible to manipulate attentional demands on three levels in the same sensory modality (Hugdahl et al., 2009). For this reason, DL is a valuable tool to assess attentional functions across the life span. In fact, there exists an undisputable age-related effect in DL performance, where younger adults outperform older adults even when controlled for hearing loss (Hommet et al., 2010). In fact, younger adults are more capable to attend to one side and inhibit stimuli from the other. However, older adults do not differ from younger subjects when instructed to report from the right side. The main age-related difference is that older adults display reduced ability to report stimuli presented to the left-ear. (Andersson et al., 2008; Hällgren et al., 2001; Jerger et al., 1994; Martin & Jerger, 2005; Westerhausen et al., 2015). Accordingly, evaluation of DL has proved helpful in studying attentional and executive processes in aging (Takio et al., 2009; Westerhausen et al., 2015).

Application of DL in dual-task studies of gait

The use of DL gives several advantages to understand gait changes in aging populations as there exists considerable knowledge on the neuroanatomical mechanisms behind DL. Nonetheless, few studies have applied DL as a cognitive task in a dual-task paradigm. Gadea and coworkers (Gadea et al., 1997) applied it in a manual dual-task, while only two other studies have used it in association with walking (Decker et al., 2017; Gorecka et al., 2018). An important peculiarity of applying DL to dual-task while walking, is that such a situation resembles the daily event in which people walk beside someone else and need to inhibit noise from the environment in order to talk to the near person from one specific side. Thus, we use The Bergen Dichotic Listening Test not only to test how auditory attention disturbs gait, but also to obtain an ecological valid alternative to current dual-task paradigms.

In the past, Decker et al. (2017) used the Bergen Dichotic Listening Task as the cognitive task in a dual-task experiment where young and older participants walked on a treadmill. However, because dual-tasking performed on a treadmill is not equivalent to regular walking (Lazzarini & Kataras, 2016), our group decided to carry out this dual-task paradigm on over-ground conditions. In this way, in 2018 we evaluated how a group of right-handed healthy older adults with varying levels of hearing loss performed DL during walking over-ground (Gorecka et al., 2018). Results showed asymmetrical effects on spatio-temporal measures of gait (i.e., step width, stride length, and gait speed) mainly on the right foot, which were modulated by hearing status. Such alterations occurred when participants focused their attention to the left-ear.

The present study

The above findings are of relevance to better understand how control of focus of attention in the auditory modality affects gait in older persons. Nevertheless, this over-ground experimental procedure has not been assessed with younger individuals. From a developmental perspective, it is important to settle the effects of an experimental situation in individuals at their highest performance capacity, which for most abilities strongly relying on sensory-motor functions is around the second and third decades of life (e.g., Leversen et al., 2012). Therefore, younger people need to be tested in this dual-task paradigm. This will allow us to broader our understanding of the methodology as well as give us a point of comparison for the effects observed in older adults.

For these reasons, in the present study, we aim to investigate possible age-related differences on this dual-task paradigm among right-handed healthy participants. To this end, we will carry out the same methodology as in our previous studies where DL is the concomitant task to over-ground walking. More specifically, we wish to investigate whether there are differences between young and older adults in the cost of the dual-task and on the percent of baseline values across the different DL conditions. Literature in the field suggest that gait parameters of younger adults are not seriously compromised by complex executive tasks, such as the go/no-go task (Beurskens et al., 2016), which could be regarded as equally demanding as the DL task. Thus, it is reasonable to expect that due to the well-functioning of sensory-motor capacities of younger adults, this group would be able to display high performance in the dual-task paradigm. Notwithstanding, the present study is exploratory in nature and DL has not been studied in over-ground conditions among younger adults. Thus, results will answer the question of whether this dual-task paradigm challenges healthy people in the same way regardless of age or whether the observed gait alterations from our previous investigation only arise in older individuals.

Method

Participants

Thirty-six healthy older adults between 63 and 80 years (*M* = 67.11, years, SD = 5.08) and forty younger controls between 19 and 35 years (M = 22.75 years, SD = 2.84) were recruited for the study. All the participants were involved in a larger umbrella project of motor functions and cognition at our institution. All were right-handed volunteers, native Norwegian speakers. Participants were free from any musculoskeletal, neurological, or cardiovascular disease with no walking difficulties, no dementia or cognitive impairment, and no history of depression. In order to control for adequate hearing function, those participants with a hearing threshold of pure tone average (PTA) of >25 dB were excluded. In addition, all participants enrolled in the study scored above 27 points in the The Mini Mental Status Examination – Norwegian version (MMSE-NR; Folstein et al., 1975; Strobel & Engedal, 2008), which ensure the inclusion of persons with normal cognitive status. Likewise, the Beck Depression Inventory II (BDI-II; Beck et al., 1988) was used in order to exclude possible depressive participants, though none of them scored within the ranges of depressive symptoms. Older adults were recruited through advertisements at the local senior citizens' center, flyers, and as well as by means of word of mouth. Younger adults were recruited from the University campus. Written informed consent was obtained from all participants. The study was approved by the local Research Ethics Committee.

Materials

Neuropsychological tests

A battery of tests was used to obtain a complete profile of the cognitive abilities of both age groups which enables to appraise the cognitive capacities of the participants and hence, better understand the results of the dual-task. Thus, the Clock Drawing Test (CDT; Shulman, 2000) was used to examine visuo-constructive abilities. To examine memory, Logical Memory I and II from Wechsler Memory Scale III (Wechsler, 1997) were used. The subtest Digit Span forwards and backwards from WAIS-IV (Wechsler, 2014) were used to examine attention and working memory. The Stroop Word Color Test (Golden, 1978) and Trail Making Test A and B (TMT; Reitan & Wolfson, 1993) were used to examine processing speed and executive functions, like inhibition and cognitive flexibility.

Background variables

Participants were interviewed about their background including education, health and disease, and daily functioning. Participants filled out the following questionnaires for laterality measures: Annett Handedness Inventory (Briggs & Nebes, 1975), and the Waterloo Footedness Inventory (Elias et al., 1998). To assess subjective assessment of physical health each subject responded to the 36 – item Health Survey (SF-36) (Loge et al., 1998; Ware & Sherbourne, 1992).

Audiometric screening

All participants completed audiometric screening using pure tone audiometry (Madsen Itera II, GN Otometrics, Denmark). Hearing sensitivity was measured calculating the Pure Tone Average (PTA) from hearing thresholds of the frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. PTA scores above 25 dB as well as an interaural difference larger than 15 dB was used for exclusion of participants.

Gait assessment

Spatio-temporal parameters were acquired using the Optogait System (Optogait, Microgate, Bolzano, Italy). The system quantifies gait parameters using photoelectric cells that register interference in light signals. The sensors in the Optogait system are placed over ground creating a seven meter long x 1.3 meter wide rectangular corridor where subjects walk in loops counter-clockwise. Ninety-six LED diodes are positioned on each bar one centimeter apart at three millimeters above the ground. When subjects pass between two bars positioned in parallel with the ground, transmission and reception are blocked by their feet. Timing, size, and distance are sensed, and spatio-temporal parameters are automatically calculated. Data were extracted at 1,000 Hz and saved on a PC using OptoGait Version 1.6.4.0 software. Gait parameters examined were gait speed, step length, and step width, for both feet (i.e., bilateral) and by foot. Variability was calculated for each parameter using coefficient of variability (CoV). All walking conditions were recorded with two Logitech web cameras from different angles to overlook any difficulties or changes during walking condition. The Optogait system has proved to be a highly reliable and valid instrument (Lee et al., 2014; Lienhard et al., 2013).

Dichotic Listening task

We applied the Bergen Dichotic Listening Test (Hugdahl & Andersson, 1986). The paradigm consists of six consonant-vowel (CV) presentations:/ba//ta//pa//ga//da//ka/where different CVs were presented simultaneously and randomized, each syllable of 350 milliseconds duration. The syllables were paired with each other in all possible combinations to form 36 different syllable pairs. From these, six homonyms pairs (e.g., ba–ba) were included in the test as perceptual control. The CVs were read by a Norwegian-speaking male voice with constant intonation and intensity with a time interval of 4000 milliseconds. The total duration of each DL condition was three minutes. DL-responses were recorded with a digital voice recorder hanging around the participants' neck. The syllables were presented using wireless noise-canceling headphones. E-prime 2.0 Software (Psychology Software Tools, Inc., Pittsburgh, PA, USA) was used to present the stimuli. The DL procedure has three conditions: The Non-Forced condition (NF) was always performed first, where participants were instructed to report the syllable they heard the clearest. For the following conditions, participants were instructed to pay attention and loudly report stimuli from either right (Forced-Right, FR) or left (Forced-Left, FL) side, while ignoring information from the opposite ear. The order of the FR and FL were counterbalanced across subjects depending on their ID number.

Procedure

The study took place at Department of Psychology, UiT Arctic University of Norway. Participants were interviewed initially to acquire their demographic background and health history. Afterward, all subjects underwent audiometric screening and neuropsychological testing in a sound-attenuated room. The dual-task experiment was conducted in a rectangular-shaped, sound-attenuated room. Participants walked within the Optogait system in a self-selected, comfortable walking speed counter-clockwise. The experimenter showed beforehand the direction of walking within the assigned area. The Optogait system started recording gait as the subject took the first footstep, initiated by a verbal signal. In the baseline condition, participants were asked to walk for one minute within the corridor. Baseline-condition was shorter than the rest of the dual-task conditions to assure that subjects did not get tired or lightheaded while allowing acquisition of enough gait data to obtain spatio-temporal parameters in the control condition. Prior to dual-task conditions, participants were given a demonstration trial of the experimental procedure. Also, participants were required to listen and respond to three CV-presentations while wearing headphones without walking, to ensure comprehension of the instructions. In the dual-task condition, subjects were asked to walk continuously and execute the DL task as accurate as possible. The instructions given were: "We ask you to say loudly the syllables that you perceived a) the clearest (in Non-Forced condition), b) from right-ear (in Forced-Right condition), c) from left-ear (in Forced-Left condition), while you walk in rounds in the designated area as previously demonstrated. Please keep walking and reporting the syllables during the entire trial as well as you can". It is important to highlight that the experimental situation did not open for any beforehand task prioritization, but rather instructions denote equal prioritization for both tasks. The dichotic stimuli was initiated simultaneously as the subject lifted a foot to initiate walking, again when the experimenter gave a verbal cue. Finally, careful adjustment of the volume was ensured for each person. Data acquisition for gait parameters in the present study were aggregated scores based on the 1-minute trial for baseline and on each 3-minute trial of the three DL conditions. Short breaks were given between conditions. The oral responses were recorded and written down by one experimenter. Afterward, the recorded responses were listened and manually inserted in the E-prime software by a second experimenter, which ensure reliable data. Laterality indexes and correct responses were calculated by the DL software. Duration of test session was approximately two hours.

Statistical analyses

All analyses were performed with the statistical package IBM SPSS Statistics 26 for Windows (IBM Corp., Armonk, N.Y., USA). Group comparisons for demographics, background variables, cognitive tests and questionnaires were performed with independent t-tests. The assessment of the effects of DL on gait was conducted through two approaches. First, we analyzed the absolute differences in raw scores by calculating dual-task cost scores (DTCs) on the mean (DTCM) and CoV (DTCCoV) of all spatiotemporal parameters. DTCs were calculated by determining the difference between gait parameters in single walking and gait parameters during the three dual-task conditions (e.g., gait scores in Baseline *minus* gait scores in NF, FR and FL). Then, DTC scores were used in statistical analyses. This first approach relying on the use of DTCs allows for a straightforward understanding of the effects of the experimental situation in *raw scores*, which is important for clinical application (Baker et al., 2009). The second approach adopted for the analysis of group differences was based on the evaluation of "percent of baseline values", which allows for group comparisons on the proportion of performance affected by the DL conditions. Percent of baseline values were calculated by dividing each gait parameter obtained under each DL condition by baseline gait scores and multiplied by 100, e.g.:

$$\textit{Percent of baseline gait speed in NFcondition} = \frac{\textit{gait speed in NFcondition}}{\textit{gait speed in baseline}} X100$$

A series of factorial analyses of variance with repeated measures in one factor were carried out to assess DL, DTCs, and percent of baseline values. For DL, we had the Group (Young, Old) as between-subjects factor while Ear (right, left) and Condition (NF, FR, FL) were the within-subjects factors. For gait data, the Group (Young, Old) was the between-subjects factor while Foot (right, left) and Condition (NF vs Baseline, FR vs Baseline, FL vs Baseline) were the within-subjects factors. In case of a significant omnibus test, univariate tests were performed. In case of significant interactions, analyses for simple main effects were carried out. For gait, we analyzed the mean and CoV separately by gait parameter as both descriptors are important to evaluate in linear measures of gait outcomes (Hamacher et al., 2011). Also, we analyzed first bilateral outcomes and then lateralized outcomes. Since asymmetries were found among older adults in our previous study (Gorecka et al., 2018), we adopted this approach to investigate possible asymmetric effects on gait parameters by DL condition. In all analyses, Greenhouse-Geisser corrections were chosen when the sphericity assumption was not met. Significant interactions or main effects involving group differences were followed up with appropriate post-hoc analyses. Due to multiple comparisons across all factorial ANOVAs, the Bonferroni correction was applied.

Statistical analyses for supplementary material

Finally, for a better appraisal of the findings reported in this study, we present raw scores for bilateral and lateralized gait outcomes as supplementary material. These data were analyzed with a set of mixed repeated measures ANOVAs using the design 4 x Condition (Baseline, NF, FR, FL) as the within-subjects factor x 2 Group (Young, Old) as the between-subjects factor. Thereafter, and in accordance with our earlier study (Gorecka et al., 2018) we conducted a series of ANCOVAs on these raw data that corrected for hearing status. The reason for focusing on hearing loss relates to various important aspects of our study. To begin with, the sensory modality of the concomitant cognitive task (DL) is hearing and older adults over 60 years of age show substantial hearing loss that need to be taken into account (Bush et al., 2015). Second, age-related hearing loss affects greatly balance and walking in the older adult (Lin et al., 2011) and third, hearing loss is tightly related to cognitive deficiencies in aging (Dupuis et al., 2015). Based on the above, "pure tone averages" (PTA) of the frequencies 500, 1000, 2000 and 4000 Hz were calculated and used as covariate in the gait analyses presented in Supplementary material.

Results

Results from demographic variables are shown in Table 1. As commonly reported, young adults had significantly more years of education than older adults. Positive measures from the Handedness Inventory and Footedness Inventory confirmed that both the old and young participants had a preference for right hand. However, we found significant group differences only on the Handedness Inventory where older adults reported to prefer the use of right hand significantly more than younger adults. No group differences were found in terms of self-reported health status or depression.

Table 1. Demographics and subjective assessments of hand and foot preference, depression scores and health status.

	Young adults (*N* = 40)	Older adults (*N* = 36)	
	14/26	10/26	
Gender (men/women)	*M (SD)*	*M (SD)*	*t*
Age	22.81(2.86)	67.11(5.09)	
Education (years)	15.40 (2.27)	13.59 (2.27)	2.77*
BDI-II	5.36 (5.84)	5.11 (4.31)	0.21
Handedness	16.63(12.25)	21.06 (3.71)	−2.08*
Footedness	7.88 (9.15)	10.86(7.72)	−1.51
SF-36	106.27 (6.68)	103.69 (6.87)	1.61

M = mean, *SD* = standard deviation (* $p < .05$). BDI-II = Becks Depression Inventory. SF-36 = Short Form Survey 36 items

Table 2. Means and standard deviations from neuropsychological tests.

	Young (N = 40)		Old (N = 36)		
Measure	*M (SD)*		*M (SD)*		*t*
MMSE-NR	29.28	(1.43)	28.92	(1.46)	1.8
CDT	6.95	(0.22)	6.81	(0.57)	1.5
TMT A	25.30	(8.2)	35.50	(17.70)	−3.28*
TMT B	65.07	(23.45)	80.04	(27.50)	−2.55*
Stroop W	107.38	(15.00)	89.08	(18.27)	4.58***
Stroop C	86.83	(11.73)	62.19	(12.06)	8.99***
Stroop WCI	59.73	(13.68)	33.83	(8.06)	9.90***
DigitSpan F	9.78	(2.14)	9.08	(2.06)	1.55
DigitSPan B	8.90	(1.65)	8.25	(2.13)	1.43
Log Mem I	11.54	(4.09)	11.36	(3.10)	.21
Log Mem II	10.54	(4.28)	15.22	(3.49)	−5.16**

M = Mean, *SD* = Standard deviation. MMSE-NR = Mini Mental Status Examination Norwegian Version. CDT = Clock Drawing Test. TMT = Trail Making Test. Stroop W = Stroop Word, Stroop C = Stroop Color, Stroop WCI = Stroop Word-Color Interference, DigitSpan F = Digit span forwards, DigitSpan B. Log Mem = Logical memory. (* $p < .05$, ** $p < .01$, *** $p < .001$)

Neuropsychological scores

Results from neuropsychological assessments are displayed in Table 2. Older adults presented significantly lower performance than the younger group on TMT A and B, as well as on all Stroop conditions. In addition, older adults recalled less information on delayed memory measures.

Hearing Thresholds

Table 3 shows hearing thresholds interaurally for both groups. As portrayed, all PTA scores were below 25 dB. Though, older adults had significantly higher hearing thresholds as compared to younger adults across all outcomes. Worst-PTA indicates actual auditory dysfunction, while best-PTA shows auditory compensation (Linssen et al., 2014).

Dichotic listening results. Three-way MANOVA showed a statistical significant main effect for Ear (F [1,74] = 60.81, p <.001, $\eta 2_p$ = 0.45) and Group (F [1,74] = 9.59, $p < .01$, $\eta 2_p$ = 0.12). No significant effect was seen for Condition. There was also a significant interaction effect between Condition x Ear, naturally due to the change in focus of attention driven by the instructions, which was expected, (F [2,73] = 17.99, $p < .001$, $\eta 2_p$ = 0.33). However, the results showed a significant interaction effect of Condition x Group (F [2,73] = 3.76 $p < .05$, $\eta 2_p$ = 0.09), indicating significant differences between older adults and young adults on some of the DL conditions. Post hoc analysis showed no significant group difference in right ear responses in any of the three conditions (see Figure 1). However, a significant group difference for correct responses from the left ear was seen in FL condition (F [1,74] = 8.38, $p < .05$, $\eta 2_p$ = 0.10, see Figure 2). The younger adults showed a REA in NF and FR and a *left-ear advantage* (LEA) in FL. In contrast, older adults showed REA in all three conditions.

Since hearing acuity differed signficantly between groups and this condition affects the perceptual ability of older participants as well as their cognitive abilities (Bush et al., 2015), we decided to control for hearing differences by conducting a factorial MANCOVA. Thus, worst-PTA, e.g., highest threshold in hearing acuity, was entered as a covariate to evaluate whether auditory deterioration influenced the observed group differences. In fact, results showed that when controlling for worst-PTA, the interaction effect on NF was no longer present (F [2,72] = 1.08, p = NS, $\eta 2_p$ = 0.02). However, the

Table 3. Mean and standard deviations for hearing thresholds in decibels (dB).

	Young (N = 40)	Old (N = 36)	
	M (SD)	*M (SD)*	*t*
PTA Right	8.09 (3.95)	14.81 (4.73)	−6.8***
PTA Left	7.03 (5.01)	14.98 (4.13)	−7.41***
PTA Best	5.85 (4.03)	13.59 (4.15)	−8.23***
PTA Worst	9.26 (4.47)	16.19 (4.32)	−6.86***

PTA = Pure Tone Average. PTA Best = Lowest threshold for both ears. PTA Worst = Highest threshold for both ears (*** $p < .001$)

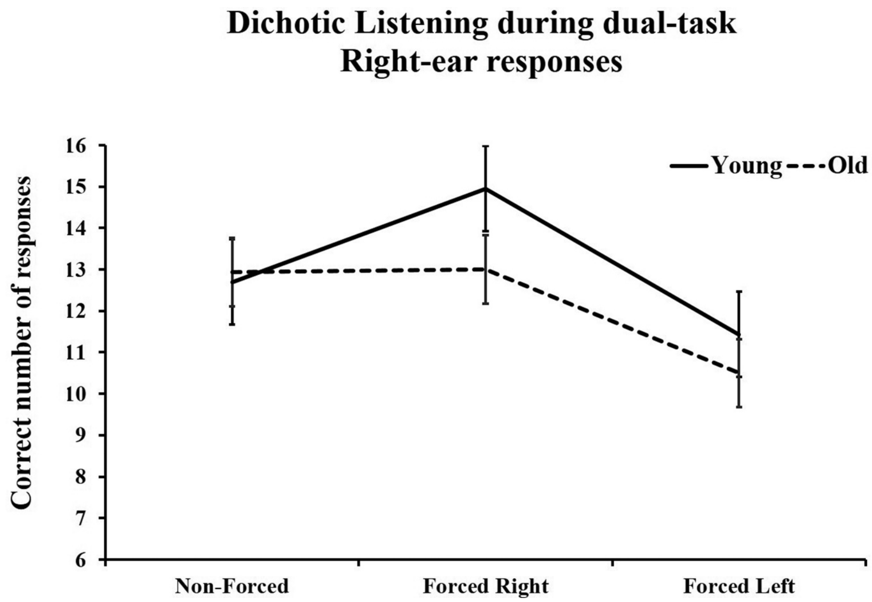

Figure 1. Mean and ± SEM for correct right-ear responses across three dichotic listening conditions.

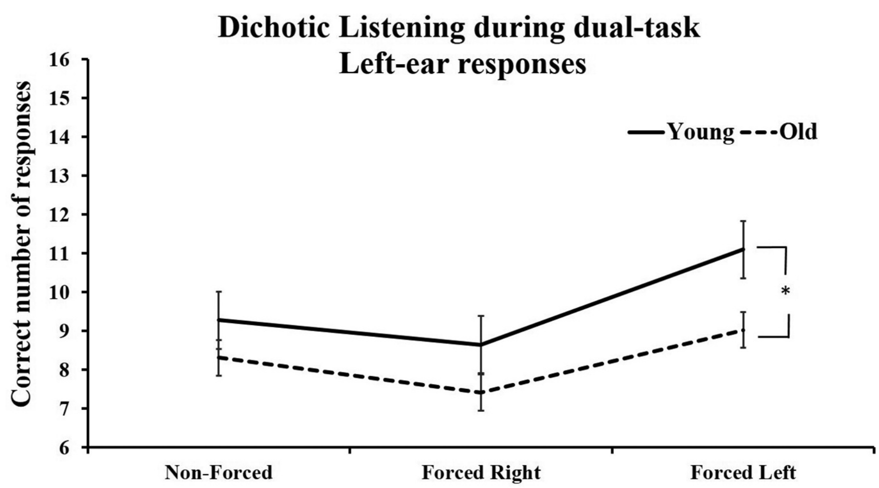

Figure 2. Mean and ± SEM for correct left-ear responses across three dichotic listening conditions. (* p <.05).

group differences were still present F [1,73] = 3.92, $p < 0.05$, $\eta 2_p = 0.05$). Post Hoc analysis showed a trend toward older adults reporting less from the left side in the FL condition (p = NS). In summary, variation in hearing acuity played a significant role in the performance of DL executed while walking.

Gait Although, the focus of all analyses in this study is on the DTCs and percent of baseline values, the bilateral raw data for gait parameters are also reported in the Supplementary Material. We highlight that results for DTCM, DTCCoV and percent of baseline values for bilateral (i.e., right and left-foot data together) outcomes and outcomes by foot (i.e., right-foot vs left-foot) were calculated and analyzed separately.

Bilateral results DTCM

Two-way MANOVA showed only a significant main effect of Condition for DTCM gait speed (F [2,73] = 12.43, $p < .001$, $\eta 2_p = 0.25$, see Figure 3) and DTCM step length (F [2,73] = 11.130, $p < .0001$, $\eta 2_p = 0.20$, see Figure 4). Additionally, a main effect for Group (F [1,74] = 43.23, $p < .0001$, $\eta 2_p = 0.36$) was also found in DTCM step length (see Figure 4). No significant main effects or interactions were found for DTCM step width.

Bilateral results for DTCCoV

For bilateral variability data we did not find any significant effect or interaction in any of the gait parameters.

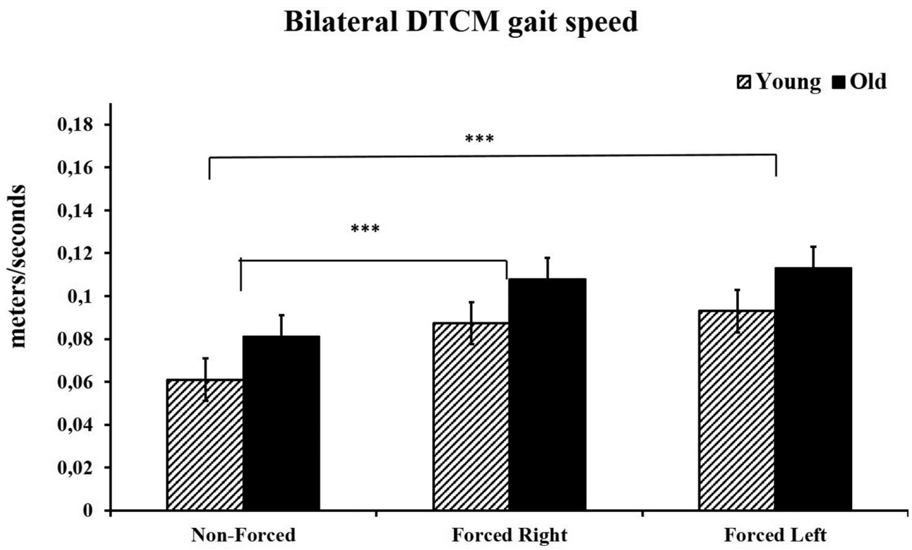

Figure 3. Mean and ± SEM for DTCM for gait speed. DTCM = Dual-task costs of mean values for bilateral outcomes (m/s). *** = $p < .001$.

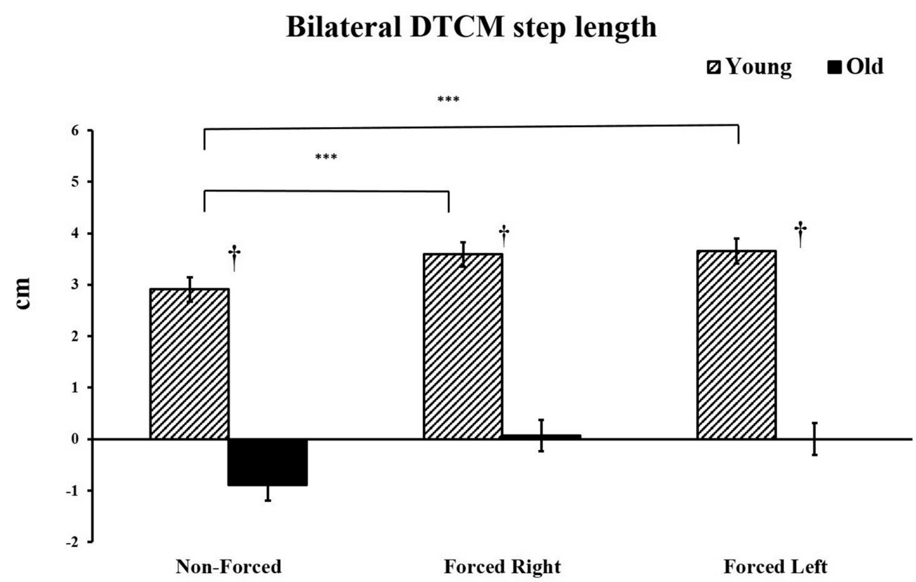

Figure 4. Mean and ± SEM for DTCM for step length. DTCM = dual-task costs of mean values for bilateral outcomes. *** $p < .001$ significant differences between conditions. † $p < .001$ significant differences between groups.

Lateralized results for DTCM

Not surprisingly, lateralized data showed similar results as in the bilateral outcomes. This regards gait speed, in which only a main effect of Condition was found (F [2,73] = 10.50, $p < .001$, $\eta 2_p = 0.22$). As in the bilateral data, the change from baseline to NF on both right and left feet was significantly lower than the cost of the dual-task in the FR and FL conditions. However, on step length we found a main effect of Group (F [1,74] = 30.79, $p < .001$, $\eta 2_p = 0.29$, see Figure 5) where younger adults displayed larger costs of the dual-tasks condition than older adults. No significant findings were found for step width.

Lateralized results for DTCCoV

As in the bilateral data, there were no significant findings for gait speed DTCCoV or step width DTCCoV. Though, step length DTCCoV showed a significant interaction between Foot and Group (F [1,74] = 7.78, $p < .001$, $\eta 2_p = 0.10$). Analyses of simple main effects demonstrated the existence of a change in variability in the young group. As depicted in Figure 6, the variability in the younger participants increased significantly on their left foot during the Forced Right condition (F [1,74] = 11.65, $p < .001$ $\eta 2_p = 0.14$, see Figure 6).

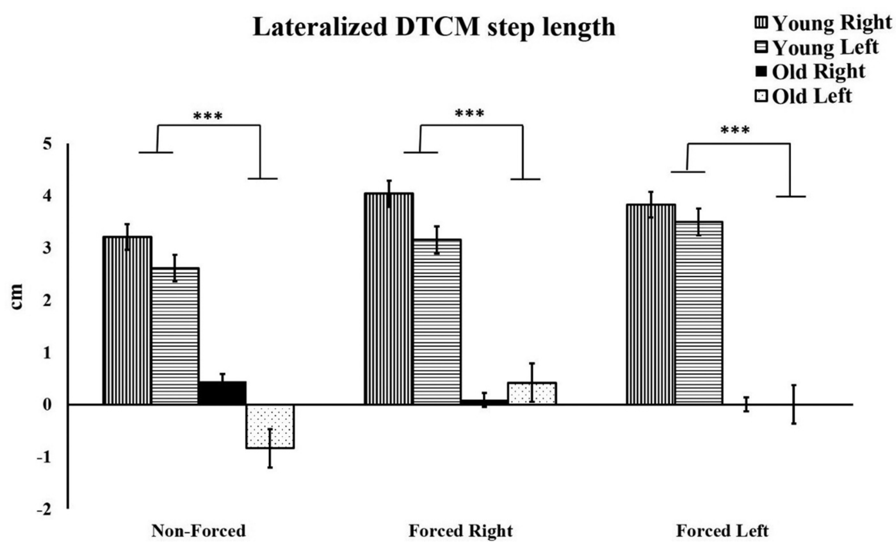

Figure 5. Mean and ± SEM for DTCM for step length by foot. DTCM = dual-task costs of mean values. *** *p* <.001 *Note*: Right/left denote right foot and left foot.

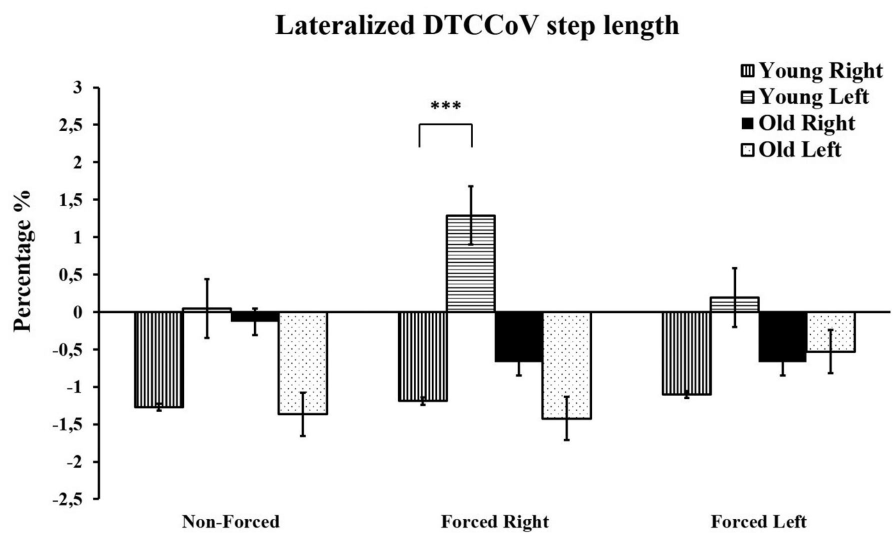

Figure 6. Mean and ± SEM for DTCCoV for step length by foot. COV = coefficient of variation; DTCCoV = Dual-task costs of coefficient of variation. *** = *p* <.001. Right/left denote right foot and left foot. Negative values indicate increased variability and positive values indicate decreased variability

Bilateral results for percent of baseline values

Mean: From these analyses, only the percent of baseline values of the mean for step length showed a main effect of Condition (F [2,73] = 8.58, p < .0001, $\eta 2_p$ = 0.19) and a main effect of Group (F [1,74] = 44.2, p < .0001, $\eta 2_p$ = 0.37). The group difference is denoted by the preserved ability of older adults in step length across DL conditions, while the younger group had a reduction of almost 5% across DL conditions. Specifically, the proportion of step length execution was mostly reduced in younger adults during the conditions where voluntary control of attention was required (FR and FL conditions). In addition, we also found a main effect of Condition for the percent of baseline values of the mean for gait speed (F [2,73] = 13.35, p < .0001, $\eta 2_p$ = 0.27). No further significant findings were obtained for the percent of baseline values of the mean for step width, see Table 4.

CoV: In these analyses we obtained a main effect of Group in the percent of baseline values of CoVs for step length (F [1,74] = 8.09, p < .006, $\eta 2_p$ = 0.10) and gait speed (F [1,74] = 7.38, p < .008, $\eta 2_p$ = 0.09). In the former, it was observed that older participants incremented their step length variability by 27% in the NF-condition as compared to baseline, while the increment for the FR and FL-conditions was of 36%. In contrast, the younger group basically preserved their step length variability across DL conditions. As for gait speed variability, we found that older adults augmented this feature by 53.7% in the NF-condition, while their increment for FR-condition was of 67.2% and of 89.5% in the FL-condition. The younger group once more showed rather a preservation of their gait speed variability across DL conditions as compared to baseline, see Table 4.

Lateralized results for percent of baseline values

Mean: These analyses showed one significant main effect of Condition for the percent of baseline values of the mean for gait speed (F [2,73] = 12.09, p < .0001, $\eta 2_p$ = 0.25). A reduction in performance of 6–7% occurred in the NF-condition, which was further reduced by 10% in the directed attention conditions FR and FL in both groups. Additionally, a significant main effect of Group on the percent of baseline values for the mean of step length was found (F [2,73] = 12.09, p < .0001, $\eta 2_p$ = 0.25). This finding replicates in much the data obtained in the bilateral analyses where the older group showed preserved execution and the younger group had decreased performance across all DL conditions, see Table 5.

CoV: In these analyses we only obtained a significant main effect of Group for the percent of baseline values for the CoV of step length (F [1,74] = 8.76, p < .004, $\eta 2_p$ = 0.11). Even though no significant interaction was observed, it was clear that some of the older adults increased their step length variability of their left foot by almost 50% and, as observed in the bilateral analyses, this group demonstrated

Table 4. Average percent of baseline by DL condition for bilateral gait parameters.

	CONDITION								
	Non-Forced		Forced-Right		Forced-Left				
	Young	Old	Young	Old	Young	Old	RMANOVA, *p-value*, *($\eta 2_p$)*		
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	Condition/Interaction/Group		
Mean									
Step length%	95.3 (4.5)	101.4 (3.3)	94.2 (5.7)	99.9 (2.3)	94.0 (5.8)	100.0 (0.0)	0.001 (0.19)	/NS	/0.001 (0.34)
Gait speed %	93.4 (8.2)	92.9 (9.1)	90.4 (11.2)	90.7 (9.5)	89.7 (11.2)	90.1 (8.7)	0.001 (0.26)	/NS	/NS
Step width%	100.1 (22.7)	119.9 (100.3)	100.0 (21.3)	116.9 (92.9)	104.2 (24.4)	125.1 (103.7)	0.02 (0.10)	/NS	/NS
CoV									
Step length%	104.8 (16.3)	127.5 (64.6)	101.4 (16.6)	136.1 (79.0)	104.2 (16.4)	136.5 (77.1)	NS	/NS	/.006 (0.1)
Gait speed%	106.1 (36.9)	153.7 (133.9)	101.9 (21.8)	167.2 (194.1)	100.6 (12.8)	189.5 (231.2)	NS	/NS	/.008 (0.09)
Step width%	101.0 (0.2)	101.0 (0.3)	101.1 (0.2)	101.1 (0.5)	101.0 (0.2)	101.0 (0.1)	NS	/NS	/NS

Abbreviations: *M* = mean; *SD* = standard deviation; RMANOVA = repeated measures multiple analysis of variance; CoV = Coefficient of Variation; Interac. = Interactions; NS = Non Significant. CoV = Calculated with the formula: [mean/SD] x 100%

Table 5. Average percent of baseline by DL condition for lateralized gait parameters (by foot).

	CONDITIONS									
	Non-Forced		Forced-Right		Forced-Left					
	Young	Old	Young	Old	Young	Old	Two-way ANOVA, *p-value*, ($\eta 2_p$)			
	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	Condition/Foot/Interaction/Group			
Mean										
Step length R%	94.8 (4.0)	99.0 (15.8)	93.5 (5.9)	99.8 (2.6)	93.8 (5.7)	100.0 (0.0)				
Step length L%	95.8 (5.3)	101.3 (3.4)	94.9 (5.9)	99.9 (2.4)	94.3 (6.2)	100.0 (0.0)	NS/	NS/	NS/	0.0001 (0.29)
Gait speed R%	93.4 (8.3)	94.8 (12.9)	90.7 (11.1)	90.7 (9.6)	90.1 (11.4)	90.1 (8.6)				
Gait speed L%	93.2 (8.7)	93.0 (9.2)	90.4 (11.4)	90.7 (9.5)	89.4 (11.6)	90.1 (9.0)	0.001 (0.25)/	NS/	NS/	NS
Step width R%	101.3 (28.5)	95.3 (141.4)	102.3 (28.4)	102.6 (114.8)	106.0 (33.9)	113.4 (127.3)				
Step width L%	101.6 (25.1)	126.0 (97.2)	101.4 (27.4)	126.4 (98.9)	105.8 (24.3)	130.7 (106.4)	NS/	NS/	NS/	NS
CoV										
Step length R%	111.1 (26.6)	110.5 (41.4)	111.2 (29.5)	126.8 (74.7)	109.7 (24.1)	131.7 (74.2)				
Step length L%	103.5 (25.1)	149.0 (98.3)	95.8 (21.1)	151.7 (101.5)	103.2 (25.8)	151.4 (95.9)	NS/	NS/	NS/	0.004 (0.10)
Gait speed R%	102.5 (17.2)	161.5 (171.1)	101.0 (16.11)	162.2 (204.8)	100.2 (13.4)	208.7 (291.3)				
Gait speed L%	107.6 (48.2)	160.1 (124.6)	102.2 (28.4)	177.7 (245.0)	100.7 (15.5)	193.4 (272.5)	NS/	NS/	NS/	NS
Step width R%	101.0 (0.2)	101.0 (0.3)	101.0 (0.22)	101.1 (0.5)	101.0 (0.2)	101.0 (0.1)				
Step width L%	101.0 (0.2)	101.0 (0.3)	101.0 (0.2)	101.2 (0.5)	101.0 (0.2)	101.0 (0.1)	NS/	NS/	NS/	NS

Abbreviations: *M* = mean; *SD* = standard deviation; CoV = Coefficient of Variation; Interac. = Interactions; NS = Non Significant. CoV = Calculated with the formula: [mean/SD] x 100%

a marked increment in variability across all DL-conditions. The younger group showed a higher increment in step length variability on their right foot, especially in the NF and FR-conditions, see Table 5.

Discussion

Effects on gait

DTC findings. The present study aimed to assess whether age-related differences existed in dual-tasking when DL was performed simultaneously during overground walking. As a whole, our findings demonstrated similar results in both younger and older adults. For instance, both groups showed larger DTCMs in gait speed and step length across all three DL conditions. Interestingly, this dual-task paradigm did not affect step width in any of the groups. Now, the DL conditions affected differently DTCM scores in both groups being the NF the one that less impacted gait. In contrast, FR and FL were more challenging as under these two conditions participants presented greater DTCs on speed and step lengths than during the NF condition.

Even though the dual-task paradigm affected gait parameters in both groups in almost the same way, there was an important age-related difference. We found that younger participants were more affected than older adults on their step length DTCM and more remarkably on the DTCCoV of the same gait parameter, as it displayed a significant lateralized difference on left foot. The bilateral data suggest that younger persons had to adjust their step length mean more during FR and FL conditions. In addition, the younger group showed a significant change on the lateralized DTCCoV scores for their left foot, which reflects a noteworthy capacity for diminished variability. To understand these results we refer to the standard interpretation of DTC scores, where negative values reflect worsened performance on dual-tasking relative to single-tasking and positive values reflect improved execution under dual-task conditions (Plummer & Eskes, 2015). Based on the above, our data indicate that younger adults are able to better regulate step length variability of their left foot when they attend to right-ear stimuli during FR condition.

Let us remind that in right-handed persons, reporting stimuli from right-ear is expected to be less effortful than reporting from left-ear (Hugdal & Westerhausen, 2016). Hence, the FR experimental situation may allow younger participants to improve their gait in order to cope with the task's demands. In the literature, it is most common to encounter that older adults show major changes in gait variability than younger people, particularly in demanding situations. However, there are data pointing to changes in variability in healthy younger adults since a certain degree of gait variability reflects a healthy organism (Hollman et al., 2016). For example, Plotnik and colleagues (Plotnik et al., 2013) showed that bilateral coordination was affected in young adults while walking slowly but not in fast walking. In line with these findings, Almarwani and coworkers (Almarwani et al., 2016) also showed that either slower or faster walking affected in a very peculiar way step variability of younger participants. These authors reported that such a change was not observed in older adults under the same conditions. Interpretation of these findings was that slower walking exerts challenges in younger people as it reduces gait automaticity and imposes higher cortical control to regulate muscular activity (Almarwani et al., 2016).

The above reports are relevant to the present study since our younger group indeed walked at a slower pace across DL conditions (see raw data in Supplementary Material). At the same time, younger participants showed their best performance for DL during the FR condition where they correctly report the highest number of correct stimuli. Taken together, it seems that younger adults recruited their available resources in FR condition to compensate for demands on walking by reducing step length variability on their left foot. This finding brings up the matter of gait asymmetries in healthy populations. Even if gait asymmetry has been usually linked to pathological states (Yogev et al., 2007; Yogev-Seligmann et al., 2008), reports about normal gait asymmetries are not uncommon in healthy people. A review by Sadeghi and colleagues (Sadeghi et al., 2000) suggests that asymmetries in healthy people raised as a natural differentiation of function between the limbs and reflect compensatory abilities. In particular, these authors proposed that the role of right-limb is that of propulsion, while the role of the left-limb is of support. Therefore, we interpret our data as an indication that younger adults are able to better control their ability for support as a compensatory process. One speculative explanation to this finding, would be that shared neural demands between both brain hemispheres exist during focusing to right-ear while walking. Roughly, the literature in laterality proposes that right-brain hemisphere specializes in language while the left-brain hemisphere specializes in non-verbal information, somatosensory and spatial functions (Zaidel, 2001). Therefore, it is possible that the findings observed in the young group are due to left-brain hemisphere handling automatic attentional focus of right-ear information, while right-brain hemisphere is modulating the contralateral side of the body to decrease step length variability and augment the support during walking. Clearly, our data cannot unveil the neural causes behind gait asymmetries in healthy people. Still, what is evident is that gait asymmetries arise in individuals without clinical conditions depending on task demands (Sadeghi et al., 2000). Our previous study with healthy older adults demonstrates this issue (Gorecka et al., 2018). Thus, the present results only corroborate that our dual-task paradigm causes asymmetric gait changes in older and younger participants, albeit not of the same nature. In older adults, there are mixed changes reflecting both deleterious effects as well as compensatory outcomes. In the present study, the asymmetric effect found in younger adults seems to be compensatory as it improves and stabilizes walking in the dual-task context.

The proportion of adjustments across DL conditions between groups: Percent of baseline findings.

Complementary to the DTC results are the group differences observed on the percent of baseline values, which allow for a different comparison across groups of retained, reduced or gained performance relative to baseline execution. These data point to the magnitude of adjustments occurring on a specific outcome and condition as compared to baseline. The most important result from these analyses regards again the step length data. We obtained group differences in the mean and CoV of percent of baseline values of step length in both the bilateral and the lateralized results. The findings indicate that for the mean, older adults preserve their ability of step length better than the younger group who had a reduction of almost 5% across DL conditions, especially during the FR and FL conditions. Nevertheless, the results from the lateralized analyses showed that the older group presented important variations in step length variability that were not present in the younger group. These data agrees with a large body of literature pointing to increase step length variability in older persons (Brach et al., 2001). The bilateral results showed an increment of 27% in the NF-condition as compared to baseline and of 36% in the directed attention conditions for the older adults, while younger participants mainly preserved their same step length variability across conditions. Additionally, the lateralized results are noteworthy in spite of the lack of significant interactions denoting asymmetries. The figures presented in Table 5 suggest the existence of important asymmetric alterations on the step length variability in *some* of the participants in both groups. This state of affairs is most noticeable for the older group. Essentially, our data document that in agreement with a vast literature (e.g., Smith et al., 2016) older persons experience a deleterious effect of performing a complex dual-task paradigm. In this case, older individuals had an increment on their step length variability of almost 50% in all conditions, being more prominently for their left foot. It is broadly acknowledged that increase step length variability is related to increased risk of falling and a sign of deleterious perturbations on gait (Rosso et al., 2014). Thus, our data confirm that older persons are more challenged from the experimental situation than younger adults are, as the younger showed an increase of variability of not more that 10% across conditions. Nevertheless, and again in spite of significant interactions, the data suggest that younger participants experience a lateralized effect on step length variability that occurred in the FR condition.

Understanding DTC findings and percent of baseline results

In the present study, we decided to employ two approaches to investigate the effects of DL during over-ground walking. The first approach regarded the evaluation of DTCs on raw scores of gait parameters, while the second approach considered the evaluation of gait modifications in percent of performance relative to baseline execution. These two approaches are important and complementary. The first approach considers dual-task effects directly on untransformed raw scores of gait, which is a strategy recommended in the gait literature for an easier interpretation and clinical usage (Baker et al., 2009). The second approach allows for a comparison between groups in terms of magnitude of effects relative to baseline due to dual-tasking. Thus, taking together information from both approaches, it is evident that the most important alteration caused by executing DL during over-ground walking is on step length variability in both groups. However, the effects are quite different. As already explained in the previous section, the younger group had a decrement of DTCCoVs on left foot that is on the “support action” during walking. These decrements on variability need to be understood as a strategy of the young group to preserve a safe walk. Thus, while DTC data demonstrate this decrement, the percent of baseline values showed a slight increment in step length variability of the younger group’s right foot, which implicates that our dual-task environment is a challenging one even for young persons in their best functional years. Concerning the older group, results from DTCs suggested little effects on their mean and CoV of step length in terms of differences across conditions in raw data. However, the percent of baseline results demonstrated that older participants actually undergo deleterious effects by performing our dual-task situation, as they have a remarkable increment in step length variability when compared to the younger participants. These findings point to an increased risk of falling (Young & Dingwell, 2012) when attending auditory stimuli while walking. All in all, the present results confirm our hypothesis that that younger persons are more prone to adapt appropriately to the dual-task situation created by DL task as this group is able to adjust their step length advantageously.

Effects on dichotic listening in relationship with neuropsychological performance

Overall results of the DL data demonstrated that younger adults showed appropriate ability to control their attention to the right or left ear, respectively, during the FR and FL conditions. They also demonstrated a clear REA during the NF condition. Conversely, the older participants showed an overall lower execution and a clear REA in all three conditions. Interestingly, the interaction observed on the FL condition where the older group had a greater difficulty to report from left-ear, disappeared after controlling for hearing status. This finding suggests that sensory loss in the auditory modality moderates exacerbated group differences in DL. However, controlling for hearing loss did not remove the main effect of group across conditions, which indicates that age differences on DL are related to normal cognitive deterioration occurring in healthy aging, such as declined executive functioning in shifting, mental flexibility, and response inhibition (Hommet et al., 2010; Hugdahl et al., 2009).

The latter statement is substantiated by results of the cognitive battery in our study, where younger adults outperformed significantly older participants on measures of executive functions and cognitive flexibility, such as the Stroop Color/Word interference task and TMT B. In addition, another significant group difference was obtained on measures of processing speed where older adults showed enlarged time to perform a task (i.e., TMT A) or limited abilities due to time restrictions (i.e., Stroop word reading and color naming). The observed age-related declines in executive function and processing speed explain group differences encountered in DL since both cognitive domains are needed to select and inhibit auditory stimuli form right or left-side during relative short intervals. It is possible that the dual-task context contributed to a more difficult environment to perform the DL conditions. Though, this situation seemed to affect both groups in the same way as group differences were constant and they agree with findings from single-task DL studies (Andersson et al., 2008; Bouma & Gootjes, 2011).

In the past, authors have suggested that poor executive function/attention and processing speed are associated with many aspects of gait decrements, and that the involvement of executive functions becomes stronger when the walking task is more challenging (Hobert et al., 2017; Martin et al., 2013; Yogev-Seligmann et al., 2008). Thus, our conjoined data from the test battery and DL task reveal that the sample of older adults displayed normal cognitive deficits on executive functions and processing speed, which explain why they had higher DTCs on the conditions where "top-down" control was required, namely on the FR and FL conditions. In sum, these results stress the importance of applying a thorough neuropsychological evaluation in dual-task studies in order to disentangle the reciprocal effects of the dual-task situation on cognition and gait.

Limitations of the study

Creating a new methodology, such as the use of DL during walking, implicates the emergence of unforeseen issues. Therefore, several limitations need to be acknowledged in the present investigation. To begin with, the lack of a single-task for DL where participants only perform the cognitive task in a sitting position is a limitation. On one hand, we wanted to evaluate the effects of the experimental situation without previous exposition to DL, and therefore, we intentionally did not assess DL as a single task. This solution is frequent in dual-task studies. For instance, the majority of the studies reported on the meta-analysis by Al-Yahya et al. (2011) did not assess single-task performances in cognition. The rationale of avoiding single-execution of DL was important to appraise the effects of this over-ground dual-task paradigm as a novelty situation. On the other hand, since the present study was part of a larger umbrella project of motor functions and cognition, the number of tasks necessary for each part of the investigation were thoroughly weighted by the ethical review board. Our argumentation about not applying DL as a single-task, was valued by the committee, especially since the research aimed to understand the effects of an ecological valid design that was not relying in previous exposition to the cognitive task. However, we acknowledge that future research should evaluate the effects on gait and cognition when participants have previous experience on DL as single-task. Since the dichotic listening task employed in this experiment is assumed not to have training effects, especially on populations who fail to show a left-ear advantage during FL condition (Hugdahl et al., 2009), the inclusion of single-task DL would allow for calculation of DTCs on all conditions.

Another potential limitation is that our subjects were not instructed to prioritize any task in this dual-task experiment. In the absence of specific instructions about which task needs to be prioritized, subjects tend to allocate attention to their gait at the expense of the cognitive test, which is a "posture-first" strategy (Shumway-Cook et al., 1997). In our study, the instructions were to perform as well as possible the DL task and walking simultaneously, which implies an equal prioritization. Nevertheless, each single participant might have prioritized differently. Further studies with our dual-task paradigm need to control for the effects of task instructions. However, we need to keep in mind that effects of task prioritization are not similar for younger and older adults (Bayot et al., 2018), as these seem to be larger in younger persons than in older individuals (Yogev-Seligmann et al., 2010). In the same way, sex differences with respect of task prioritization have been reported (Bayot et al., 2018), which complicates further this matter. The unclear effect of task prioritization in younger and older adults and in males and females may pose an extra challenge to the experimental situation when trying to compare outcomes from both groups and from both sexes. Because DTC in dual-task experiments are influenced by several factors, among them instruction of task priority, future experiments need to evaluate the effects of task instruction in specific groups of individuals, such as for example, younger vs older males or younger vs. older females.

Finally, it is necessary to acknowledge a limitation on the gait methodology. In most dual-tasks studies with gait, subjects are required to walk linearly on a gait device, while in our experimental situation subjects need to walk straight as well as negotiate the turns to follow the path in the walking area. Since the design of the present study intended to be as ecologically valid as possible, we decided to allow subjects to walk as in real life, that is continuously, and obtained global gait measurements from this design. Based on the results of the present study, we realized that such an environment poses different challenges to different populations and it is possible that a more traditional setting would show different results. Thus, future studies are encouraged to apply other dual-task settings to evaluate whether the present findings rely on the sole use of DL, independent of walking environment, or whether gait alterations due to DL are tightly related to the walking situation.

Conclusion

The current study has employed a novel approach to the dual-task paradigm using a DL task to investigate the interplay between, gait, sensorimotor abilities, and lateralized attentional constraints in healthy younger and older adults. The present data reveal that our dual-task paradigm induces asymmetric adjustments on gait in younger adults. However, these gait asymmetries differ from findings reported in our earlier study where older adults with different hearing status were assessed. In the present study, asymmetric gait changes in younger participants seem to arise as compensatory mechanisms rather than being detrimental for the execution of the dual-task. This finding is relevant to expand our knowledge about asymmetries in healthy populations. To date, gait asymmetries have not been widely studied in healthy adults (Morris et al., 2016), and certainly not in association with concrete cognitive demands in one sensorial modality like DL. Furthermore, the present study confirmed that older adults experience considerably higher step length variability than younger persons in a novel and complex dual-task situation. Future studies are encouraged to employ this paradigm on healthy populations on different life phases, such as middle-age persons or teenagers in order to expand our understanding of gait asymmetries and attentional control along the life span.

Acknowledgments

We thank Johan Jacob Espenes and Jesper Gundersborg Ansethmoen for helping with data acquisition.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Financial support was received from the Faculty of Health Sciences, UIT- Arctic university of Norway (2016/5455), Norway and from the Norwegian Health Association (Nasjonalforeningen for folkehelsen) (2014/888)

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