Gait & Posture 67 (2019) 262–268

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

The effect of simultaneously and sequentially delivered cognitive and aerobic training on mobility among older adults with hearing loss

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ARTICLE INFO

Keywords:
Motor aging
Auditory aging
Balance
Cognitive compensation

ABSTRACT

Background: Older adults exhibit declines in auditory and motor functioning, which are compensated for through the recruitment of cognitive resources. Cognitive or physical training alone has been shown to improve cognitive functioning and transfer to motor tasks, but results are mixed when these are combined in studies of healthy older adults, and few studies have included those with age-related hearing loss (ARHL), who are at a higher risk of falls.

Research question: To examine format effects in mixed training, we used a repeated measures intervention design to compare the efficacy of Simultaneous and Sequential multimodal training formats.

Methods: 42 older adults (M_{age} = 68.05, SD_{age} = 4.65, females = 26) with (ARHL) and without hearing loss (OAH) completed an intervention study consisting of 12 sessions of multimodal training (computerized cognitive dual-task and recumbent aerobic cycling). Participants were randomly assigned to either the Simultaneous (concurrent cognitive and aerobic) or Sequential training group (cognitive followed by aerobic) and completed assessments of single- and dual-task mobility concurrent with an auditory working memory task. Training gains were assessed with repeated measures ANOVAs using magnitude of improvement from pre- to post-training on primary outcome measures as the dependent variable.

Results: Gains in auditory working memory were greater in the Sequential group than Simultaneous particularly among OAH. ARHL participants were unaffected by format. While all participants improved on a measure of chair rises, there was no benefit to standing balance. The results demonstrate an advantage to Sequential training, suggesting a benefit to focusing on each task in isolation.

Significance: The gains noted in the ARHL indicate the potential benefit of incorporating cognitive remediation into traditional audiological rehabilitation. Moreover, it is important to consider the cost of dividing attention when combining training.

1. Introduction

Age-related declines in sensorimotor and sensory functioning appear to be partially countered with the recruitment of cognitive executive processes (Cognitive Compensation) [1]. This compensation is more pronounced among those with age-related hearing loss (ARHL), who are at a higher risk of falls [2]. Cognitive remediation techniques, such as cognitive training [3] and exercise [4] can enhance cognitive functions and consequently, improve mobility and posture [3]. Combined multimodal physical and cognitive training appears to be superior to unimodal training in some, but not all cases [5,6]. The present study extends this multimodal approach to older adults with mild hearing loss.

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https://doi.org/10.1016/j.gaitpost.2018.10.020
Received 7 February 2018; Received in revised form 6 October 2018; Accepted 15 October 2018

1.1. Hearing and motor aging

There is an increasing interdependence between cognitive and both auditory and motor functioning with aging [1]. Within the domain of hearing, sensory challenges such as background noise [7] and low signal intensity [8] are more detrimental to older than younger listeners' working memory (WM) and executive functioning. Executive functions have also been implicated in balance and gait in old age, as shown in cognitive-motor dual-task studies [9]. While a simple cognitive task can sometimes facilitate postural performance (i.e., *U-Shaped Non-Linear Interaction Model*), dual-task costs typically occur with increasing task complexity. According to the *Task Prioritization Model*, the nature of these costs depends on the novelty and type of motor task, complexity of the secondary cognitive task, and degree of postural reserve and hazard estimation [10]. When costs are observed in the cognitive domain, this tendency to prioritize posture is often referred to as the posture-first principle [11]. Dual-task costs are exacerbated among ARHL individuals, who demonstrate greater cognitive dual-task costs in challenging balance conditions compared to normal-hearing controls [12,13]. Similarly, gait is negatively impacted by hearing loss, particularly in dual-task conditions [14]. Since cognitive capacity is recruited to support performance in both motor and auditory domains, cognitive training might improve dual-task performance, particularly among ARHL individuals.

1.2. Cognitive remediation

Executive function training has been used to address age-related declines in working memory and executive functions [15], which are integral to activities of daily living [16]. This type of training also benefits motor tasks such as gait speed and balance under dual-task conditions in healthy older adults [3,17]. Another approach to cognitive remediation involves exercise training, which benefits executive functions, attentional control [4] and single- and dual-task gait speed [18].

Recent training studies have examined multimodal training (exercise plus cognitive training) to maximize gains in healthy older adults [5], MCI, and dementia populations [19] typically using two formats: Simultaneous training wherein a motor and cognitive task are performed concurrently, and Sequential training wherein the two training modes are performed consecutively. Simultaneous training can be more advantageous as it is more comparable to real-life situations, reduces training time and costs [20], and trains coordination between cognitive and physical components [6]. However, Simultaneous formats risk taking attention from the cognitive task [21], while Sequential training allows participants to focus on both tasks under full attention.

The efficacy of multimodal training compared with single domain (cognitive or physical) training is mixed although some have demonstrated transfer to everyday functioning [22,23]. Others have demonstrated increased efficacy of Sequential [6] and Simultaneous training [5] on dual-task outcome measures with improvements observed on the cognitive task, motor task, or both [5,24]. Others failed to find synergistic benefits from sequentially combined physical and cognitive training after tri-weekly training for 12 weeks [25].

In sum, while many studies using a multimodal training approach have demonstrated an improvement on some aspect of dual-task performance, the heterogeneity of methods makes comparisons between studies challenging [5]. To date, no study has directly compared the effects of Sequential and Simultaneous training formats on dual-task mobility. Additionally, no studies have examined the effect of cognitive remediation on dual-task mobility in older adults with ARHL [14].

1.3. Current study

We aimed to compare the effects of Sequential and Simultaneous formats of multimodal cognitive and exercise training on cognitive-motor dual-tasking in older adults with and without mild hearing loss. Older adults underwent aerobic exercise training and computerized dual-task training, either sequentially or simultaneously. Given that the efficacy of each training component has been previously established [e.g., 4,17], we omitted a control group. Single-and dual-task measures of postural control and mobility were primary outcome measures and included two levels of listening challenge.

Objectives and Hypotheses. Due to the increasing involvement of cognitive resources in hearing with aging, we considered a sub-sample of older adults with mild hearing loss and hypothesized that these individuals would demonstrate dual-task training gains on the primary outcome measures, particularly in challenging auditory conditions. We also hypothesized that all participants would demonstrate dual-task gains on the primary outcome measures, but based on the literature which shows age-related increases in cognitive-motor DT costs [9,11], the Sequential group would show larger gains than the Simultaneous group, due to the advantage of training each task under full attention.

Methods

Participants

To achieve a power of .80 at a significance level of $p < .05$ for the group by time interaction, we aimed to test 20 participants per group to allow for attrition. A total of 42 older adults ($M = 68.05$ years, $SD = 4.65$, females = 26) were recruited through a participant pool and newspaper advertisements by research staff. Exclusion criteria included progressive medical conditions, use of medications affecting cognition or balance, use of hearing aids, and suspected presence of mild cognitive impairment as defined by the Montreal Cognitive Assessment (MoCA $<$ 26/30) [26]. Cardiovascular health was assessed with the Jones protocol [27]. Participants were excluded if they presented with cardiac symptoms or an elevated heart rate. Of the 85 participants recruited, 42 eligible participants were randomly assigned to the training groups by the research coordinator based on the time at which they were recruited into the study. Participants received an honorarium for their participation. To investigate the impact of hearing status on training gains, participants within each training format were classified by hearing status, resulting in four groups: ARHL Sequential ($n = 7$), ARHL Simultaneous ($n = 6$), OAH Sequential ($n = 15$) and OAH Simultaneous ($n = 15$). There was no participant attrition.

1.4. Materials

1.4.1. Screening and background

A health and demographics screening was administered by telephone. Eligible participants underwent in-person background tests. Measures used for screening are marked with an asterisk.

1.4.2. Cognitive measures

Global cognitive functioning was assessed using the Montreal Cognitive Assessment * [26]. Cognitive processing speed and working memory were assessed using the Coding (Digit Symbol) and Letter Number Sequencing (LNS) subtests of the Wechsler Adult Intelligence Scale [28] respectively. Executive functioning was measured using the Stroop Task [29] as an assessment of response inhibition (number of correct responses divided by total completion time).

1.4.3. Hearing measures

Air-conduction pure-tone audiometry was administered to assess auditory acuity (Maico MA 42). Participants were presented with pure tones at varying frequencies (250–8000 Hz) following standard procedure, from which pure tone average (PTA) hearing thresholds were derived (500, 1000, 2000 and 3000 Hz) averaged across both ears. Participants were classified as having normal hearing: OAH with PTA thresholds below 25 dB HL (decibel hearing level), or with mild hearing

loss: ARHL, with PTA thresholds between 25 and 40 dB HL. Subjective hearing was assessed using the Listening Self-Efficacy Questionnaire [LSEQ: 30].

Physical measures

The Activities-Specific Balance Confidence Scale "ABC Scale" [31] assessed self-reported balance confidence. The Jones Test [27]* was performed on a stationary bike, as a sub-maximal estimate of maximum heart rate.

Training Tasks

Dual-task (DT) Training

The DT training task [32] was adapted for iPad use (MD785CL/BIOS 8.2) and is described elsewhere [32,33]. Each of the two tasks involved the presentation of a central figure (e.g., fruits, vehicles), to which participants responded by pressing the corresponding button (see Supplementary Figure 1). Response times and errors were recorded [33]. Blocks of single- and dual-task trials were given, with individualized and continuous feedback. Each session lasted approximately 30 min.

1.4.4. Physical training

The aerobic training component involved recumbent cycling, chosen to minimize balance demands. Physical workload was increased from 40% of baseline estimated maximum heart rate in Sessions 1–4, to 44% in Sessions 5–8, and to 48% in Sessions 9–12. Each training session lasted 35 minutes (5 min. warm-up, 25 min. at target heart rate, 5 min. cool-down).

1.5. Outcome measures

Four different motor tasks were performed singly (A) and concurrently (B) with a cognitive task described below under both low and ideal conditions. Participants completed two trials per condition in an ABBA format.

1.5.1. Sit-to-stand task

The Sit-to-Stand task [34] indexed global mobility, defined as time (s) to complete five chair rises with arms crossed.

1.5.2. Balance task

Balance was assessed using a NeuroCom Equitest apparatus (computerized dynamic posturography). Participants completed three conditions: double support, visual sway-referenced (i.e., visual surround moves synchronously with AP sway), and single-support (i.e., balancing on their preferred leg). Each trial was 30 s and the outcome measure was the ellipse area (mm^2).

1.5.3. Cognitive task

The auditory working memory "*n*-back" task [35] served as the cognitive outcome measure. In each trial, participants were presented with fifteen pseudo-randomly ordered (without consecutive repetition) single digit numbers between one and ten excluding the two-syllable numeral seven. The stimuli were presented via insert headphones (E-A-RLINK 3A) at 35 dB HL above each participant's average pure-tone threshold. Participants were asked to report the number presented one item prior to the currently presented number (1-back). To increase auditory challenge, half the trials were presented more quietly (i.e., 20 dB HL above the average pure-tone threshold; 12). The number of correct responses was averaged across trials in each condition.

1.6. Procedure

Participants underwent two pre-assessment sessions. First, they were administered the neuropsychological measures. In Session 2, they underwent the physical assessment (blood pressure, height, weight, heart rate, and sub-maximal VO_2) and baseline testing on the *n*-back task. The experimental tests of single- and dual-task auditory working memory and balance were given. Three short warning beeps preceded each trial, and one short beep signaled the end of each trial. The experimental procedure was performed under both listening conditions, in counterbalanced order.

Training was administered in blocks of four to seven people who met twice per week for six weeks. Once one cohort had completed training, a new one began. The Simultaneous training groups performed both training tasks at the same time (30 min total), while the Sequential training group first performed the iPad training task (30 min) followed by recumbent cycling (30 min). Both groups completed identical post-training assessments. Personnel involved in training were different from those conducting assessments to remain blind to treatment condition.

1.6.1. Planned analyses

Analysis of the primary outcome measures was performed using repeated measures mixed factorial ANOVAs. Where appropriate, multiple tests were Bonferonni corrected and otherwise, results were considered significant at $p < .05$.

2. Results

2.1. Data screening

All background and baseline experimental measures were checked for outliers (i.e., > 3.5 SD) both in terms of intra- and inter-individual variability and extreme scores were winsorized. Additionally, a square root transformation was applied to non-normally distributed variables. One participant had extreme posture scores, leaving 21 participants in the Simultaneous group and 20 participants in the Sequential group. Six participants were excluded due to difficulty performing the single-support task, leaving data from 18 and 17 participants in the Simultaneous and Sequential groups, respectively.

2.2. Baseline assessment

Background and baseline experimental measures are shown in Table 1. One-way ANOVAs with Bonferroni corrected contrasts were conducted to compare the four training groups at baseline, confirming that beyond differences in PTA (ARHL > OAH), the groups did not differ significantly on any other background or baseline experimental measures ($p_s \geq 0.103$).

2.3. Dual-task training

To confirm the efficacy of cognitive training, changes in dual-task reaction times and error rates were analyzed across three phases of training pooling all participants ($n = 41$). There was a significant main effect of time for reaction times, $F(2, 42) = 91.76$, $p = < .001$, $\eta_p^2 = 0.814$, 95% CI [0.69, 0.86], and error rates, $F(2,76) = 14.63$, $p < .001$, $\eta_p^2 = 0.28$, 95% CI [0.11, 0.41]. Contrasts revealed improvements on both measures from early to late phases ($p_s < .001$), replicating previous work [36].

2.4. Change scores

Change scores for all primary outcomes were calculated by subtracting baseline scores from post-training scores.

Cognitive task. To assess training related effects in the cognitive domain, a Group (ARHL Sequential vs. ARHL Simultaneous vs. OAH Sequential vs. OAH Simultaneous) × Balance (seated vs. STS vs. double support vs. visual vs. single support) × Listening Level (ideal vs. low) mixed factorial ANOVA was performed using *n*-back task change scores (Fig. 1, Table 2). A main effect of balance was observed, $F(4,$

Table 1
Means and standard deviations for all baseline background and experimental measures.

Source	*Sim OAH* (*n* = 15)	*Seq OAH* (*n* = 15)	*Sim ARHL* (*n* = 6)	*Seq ARHL* (*n* = 7)	*p value*
Age (years)	67.27 (4.32)	67.77 (3.35)	70.50 (5.09)	70.14 (7.80)	.403
Education (years)	17.40 (3.07)	15.73 (2.96)	15.17 (1.33)	17.00 (2.65)	.273
PTA (dB)	19.44 (4.72)	15.90 (7.25)	29.72 (4.36)	27.62 (2.38)	< .001
MoCA (max. 30)	27.67 (1.59)	27.38 (1.76)	26.33 (1.63)	27.62 (2.38)	.103
LNS (max. 30)	19.33 (2.35)	19.00 (2.48)	19.17 (0.75)	18.14 (2.19)	.705
DS (max. 135)	67.40 (11.91)	65.08 (13.28)	64.50 (21.23)	62.71 (9.69)	.890
Stroop CN (# correct/s)	1.33 (0.35)	1.16 (0.28)	1.15 (0.16)	1.29 (0.34)	.461
Stroop WR (# correct/s)	0.90 (0.21)	0.75 (0.12)	0.75 (0.22)	0.81 (0.17)	.146
ABC (max. 100)	94.78 (6.17)	96.93 (2.85)	96.48 (3.94)	91.88 (7.42)	.238
LSEQ (max. 100)	84.78 (10.08)	89.07 (9.37)	78.61 (17.65)	82.46 (8.56)	.279
STS (seconds)	9.50 (2.74)	10.65 (2.78)	10.81 (2.79)	10.35 (3.00)	.669
N-back (# correct)	13.67 (1.05)	12.61 (2.33)	14.00 (0.00)	13.14 (1.07)	.209
DS (mm^2)	125.91 (126.99)	190.29 (263.16)	258.24 (383.02)	124.96 (109.40)	.602

Note. Sim OAH = simultaneous healthy older adults. Seq OAH = sequential healthy older adults. Sim ARHL = simultaneous older adults with age-related hearing loss. Seq ARHL = sequential older adults with age-related hearing loss. PTA = Average Hearing Threshold pooled. MoCA = Montreal Cognitive Assessment. LNS = Letter-Number Sequencing. DS = Digit Symbol. Stroop CN = Stroop Color Naming. Stroop WR = Stroop Word Reading. ABC = Activities-Specific Balance Confidence Scale. LSEQ = Listening Self Efficacy Questionnaire. STS = Sit-to-Stand. DS = double support.

Table 2
Mean performance on the n-back, Sit-to-Stand and standing balance tasks.

Condition	Sequential (*n* = 20)		Simultaneous (n = 21)	
	Pre	Post	Pre	Post
N-back task (# correct)				
Single-ideal	12.80 (1.96)	13.40 (1.43)	13.76 (0.89)	13.86 (0.36)
Single-low	9.20 (3.46)	12.15 (3.40)*	11.10 (3.58)	11.00 (4.14)
Dual-STS-ideal	11.95 (2.08)	13.28 (1.53)*	12.88 (1.07)	12.81 (1.34)
Dual-STS-low	6.88 (4.21)	10.22 (3.21)*	8.24 (3.92)	8.31 (4.24)
Dual-DS-ideal	13.40 (1.22)	13.85(0.56)*	13.62 (0.65)	13.90 (0.26)*
Dual-DS-low	8.73 (4.37)	11.48 (3.34)*	10.57 (4.14)	10.07 (4.54)
Dual-visual-ideal	13.58 (1.04)	13.60 (0.62)	13.81 (0.49)	13.83 (0.46)
Dual-visual-low	9.00 (4.33)	11.28 (3.10)*	10.07 (4.12)	10.50 (4.33)
Dual-SS-ideal	13.50 (1.55)	13.63 (0.62)	13.94 (0.24)	13.89 (0.32)
Dual-SS-low	9.75 (3.94)	11.87 (2.70)	11.72 (3.87)	9.72 (4.78)
Sit-to-Stand (seconds)				
Single	10.74 (2.80)	10.61 (3.34)	9.83 (2.55)	9.76 (2.59)
Dual-ideal	13.17 (3.29)	11.85 (3.19)*	11.29 (2.42)	10.75 (2.31)
Dual-low	13.83 (4.19)	12.20 (3.41)	12.08 (2.42)	11.11 (2.93)
Standing Balance (mm^2)				
Single-DS	167.43 (220.32)	202.00 (256.88)	163.72 (227.41)	125.60 (154.99)
Dual-DS-ideal	96.59 (72.32)	166.07 (240.12)	138.21 (186.65)	134.63 (167.35)
Dual-DS-low	227.57 (378.07)	133.16 (133.78)	103.76 (156.31)	120.46 (89.11)
Single-visual	442.72 (797.51)	296.91 (326.28)	208.93 (228.65)	155.76 (113.96)
Dual-visual-ideal	175.36 (149.07)	242.99 (309.26)	159.96 (141.71)	139.67 (107.98)
Dual-visual-low	225.62 (268.43)	262.13 (293.29)	177.70 (225.38)	113.75 (69.57)
Single-SS	2240.95 (4770.86)	908.40 (908.98)	969.28 (1622.88)	1056.82 (1379.00)
Dual-SS-ideal	887.06 (977.53)	710.77 (636.58)	572.89 (486.92)	835.17 (738.61)
Dual-SS-low	1142.05 (1980.11)	726.51 (955.91)	910.02 (1638.60)	550.50 (288.07)

Note. * denotes a statistically significant change from pre to post at $p < 05$. STS = Sit-to-Stand. DS = double support. SS = single support.

116) = 3.64, $p = 0.008$ $\eta_p^2 = 0.11$, 95% CI [0.01, 0.20], with follow-up contrasts indicating greater gains in stable ($M = 0.76$, $SE = 0.45$) and visual ($M = 0.83$, $SE = 0.44$) conditions compared with single support ($M = 0.00$, $SE = 0.47$). The main effect of group, $F(3, 29) = 5.04$, $p = 0.006$, $\eta_p^2 = 0.34$, 95% CI [0.04, 0.51], was also significant, and was qualified by a significant interaction of group and listening level, $F(3, 29) = 4.15$, $p = 0.015$, $\eta_p^2 = 0.30$, 95% CI [0.01, 0.47]. Follow-up one-way ANOVAs were performed separately for each listening condition: With low volume, there was a statistically significant effect of

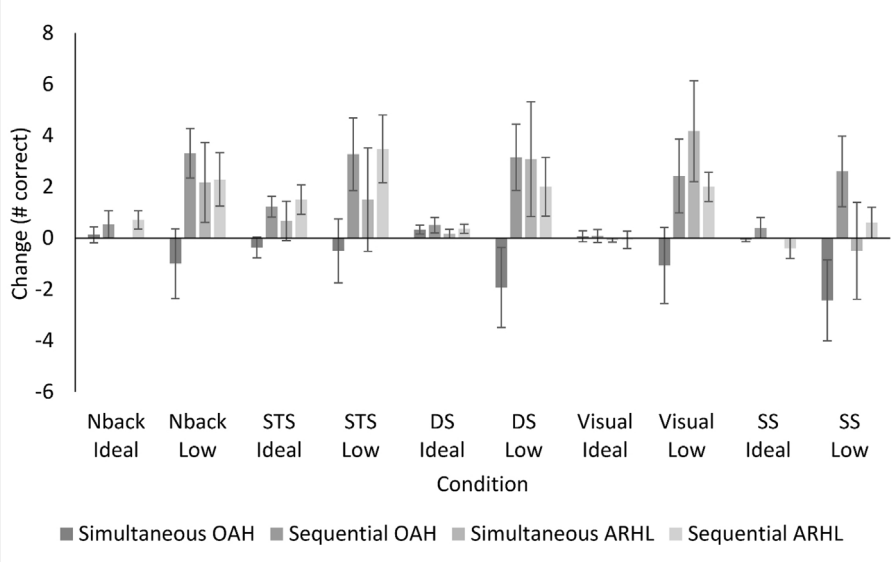

Fig. 1. Change scores for the *n*-back task performed during the standing balance tasks and the STS divided by four groups. *Note.* Error bars represent one standard error of the mean. STS = Sit-to-Stand. DS = Double Support. Visual = Visual sway-referenced. SS = Single Support.

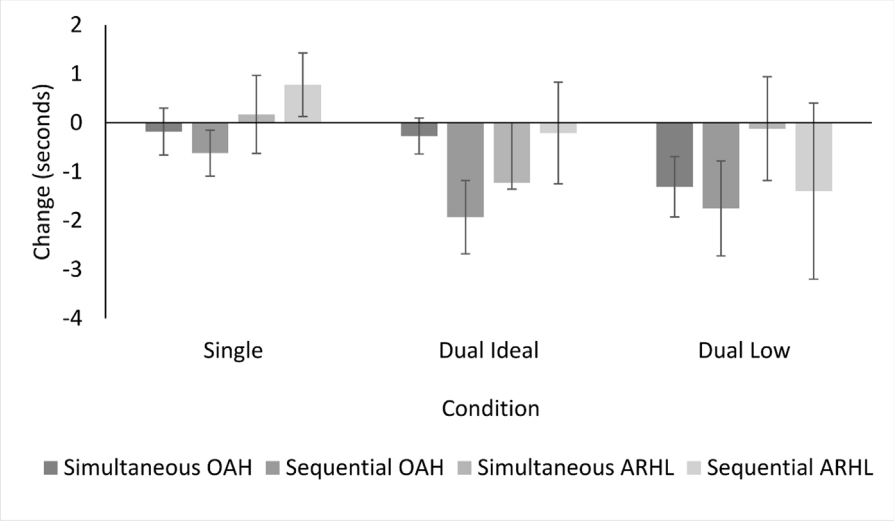

Fig. 2. Change scores for the Sit-to-Stand Task. *Note.* Negative values indicate a reduction in completion time and improvement in performance. Error bars represent one standard error of the mean.

group, $F(3,32) = 221.88$, $p = .008$, such that the Sequential OAH group ($M = 4.08$, $SE = 1.25$) improved more than the Simultaneous OAH group ($M = -2.01$, $SE = 1.06$), $p = .005$. All other group contrasts were non-significant ($p \geq 0.554$) and a similar pattern was not observed in ideal listening conditions ($p = 0.170$). There was also a trend in the data such that the ARHL group improved post training regardless of format.

Sit-to-Stand. A Group (4) × Challenge (Single vs. Dual-Ideal vs. Dual-Low) mixed factorial ANOVA was performed using change scores in timed performance (Fig. 2, Table 2). A significant main effect of challenge was observed, $F(2, 74) = 4.29$, $p = 0.017$, $\eta_p^2 = .0.10$, 95% CI [0.01, 0.23], such that completion times decreased more over time in Dual-Ideal ($M = -0.91$, $SE = 0.40$), $p = .028$ and Dual-Low ($M = -1.14$, $SE = 0.55$), $p = .021$ conditions compared with Single-Task conditions ($M = -0.037$, $SE = 0.30$).

Standing balance. To assess change on the Equitest task, a Group × Balance (stable vs. visual vs. single support) × Challenge (Single vs. Dual-Ideal vs. Dual-Low) mixed factorial ANOVA was performed using change in ellipse areas (Fig. 3, Table 2), revealing non-significant effects ($p \geq 0.415$).

3. Discussion

The purpose of the current study was to compare the effects of Sequential and Simultaneous formats of cognitive and exercise training on the primary outcome measures of cognitive-motor dual-tasking (*n*-back, sit-to-stand, balance task).

3.1. Auditory working memory gains

As hypothesized, sequentially trained participants demonstrated significant gains on the auditory working memory task under dual-task conditions. In contrast, the Simultaneous group did not demonstrate similar gains, suggesting a cost associated with dividing attention during training. Support for this interpretation is found in the cognitive training data, where the Sequential group outperformed the Simultaneous group, if only numerically [33]. By contrast, group equivalence was observed on both subjective (Borg Scale; $p = .509$) and objective (mean power output in Watts; $p = .833$) measures of physical workload. This overall pattern is consistent with postural prioritization [11], in that the cost of dividing attention during training was observed

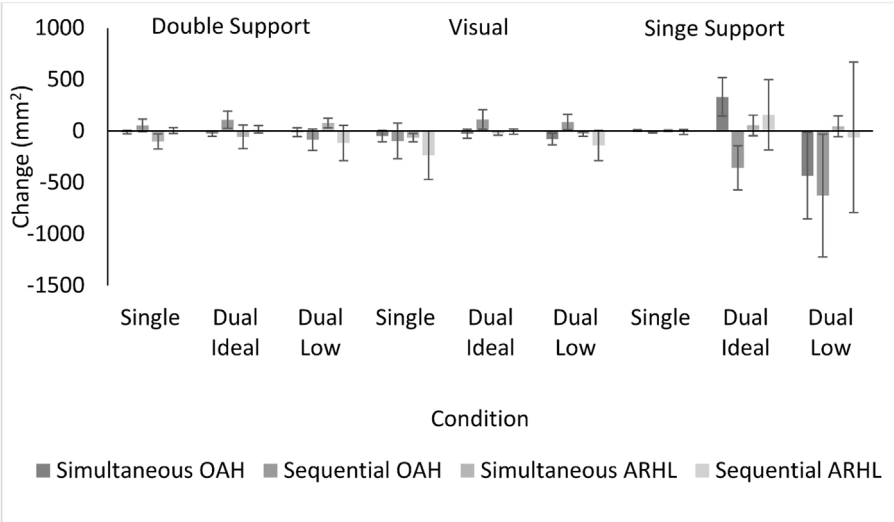

Fig. 3. Change scores for the standing balance tasks (ellipse area). *Note.* Error bars represent one standard error of the mean. DS = Double Support. SS = Single Support.

on the cognitive rather than the physical task. This pattern was likely influenced by the complexity of the cognitive training task (i.e., *U-Shaped Non-Linear Interaction Model)*. Moreover, according to the *Task Prioritization Model*, other factors which were not explicitly measured (e.g., novelty of the physical training task) may also have contributed to these findings [10]. The Sequential training group also demonstrated larger gains on an independent measure of working memory (LNS) than the Simultaneous group [33].

As anticipated, hearing status influenced training gains. The ARHL participants appeared to benefit from training regardless of format. These gains were most apparent in the low volume listening conditions, which has been shown as detrimental to older adults' auditory WM performance [8]. Pairing a challenging auditory and motor task exacerbated these costs [12]. Strengthening cognitive resources through training may have enabled these participants to better compensate for age-related hearing loss.

3.2. Motor outcome measures

Consistent with previous work, both groups demonstrated improved performance on sit-to-stand performance under dual-task conditions [36,37]; however, no pre-post improvements were observed for the measures of balance. These findings may be explained using the concept of postural prioritization. Specifically, if older adults were prioritizing posture throughout the assessment sessions, the cognitive training might have freed up capacity for the lower priority cognitive task. This pattern echoes previous work on balance and walking, in which training reduced brain activation during imagined motor tasks, freeing resources up for secondary cognitive tasks [38].

3.3. Limitations and future directions

A limitation of the study is that our sample consisted of healthy older adults and individuals with only mild hearing loss. Future studies could include older adults with more severe hearing loss or fallers. Regarding study design, the order of cognitive training and exercise in the Sequential group was not counterbalanced (cognitive was given first). This was done to enable participants to quickly transition from cognitive to exercise training [39]. Further, total training time differed between the groups, although this was done to equate the "dosage" of each training activity across formats. Another issue is the absence of ecological measures of dual-task gait or balance which could provide information regarding the transferability of training to everyday functioning.

4. Conclusions

The current work extends the multimodal training literature and provides new experimental evidence on how to optimize training, particularly for those with ARHL. When combining cognitive and physical training, it is important to consider the cost of dividing attention, which may detract from cognitive performance gains. Current audiological rehabilitation focuses on amplification, environmental support, and listening training. The current study suggests that cognitive training may be beneficial to those with hearing loss, particularly during complex listening conditions.

Funding

This work was supported by a Canadian Institutes of Health Research (CIHR) grant awarded to KZHL, NSO, LB, and three others (MOP-123302). The funding source had no role in study design, analysis and interpretation of the data or in writing and submitting the manuscript.

Declaration of interest

None.

Ethics

The work has been approved by Concordia University and the PERFORM Centre's ethical committees and all subjects gave informed consent to participate.

Acknowledgements

This work was supported by a Canadian Institutes of Health Research grant awarded to KZHL, NSO, LB, and three others (MOP-123302). We also thank Matthew Davis and Daniel Aponte for their assistance with data collection and management, and Christina Weiss and Amanda Rizk for assistance with training and cardio screening.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gaitpost.2018.10.020.

References

[1] K.Z.H. Li, U. Lindenberger, Relations between aging sensory/sensorimotor and cognitive functions, Neurosci. Biobehav. Rev. 26 (7) (2002) 777–783.
[2] A. Viljanen, J. Kaprio, I. Pyykkö, M. Sorri, S. Pajala, M. Kauppinen, T. Rantanen, Hearing as a predictor of falls and postural balance in older female twins, J. Gerontol. Series A: Biol. Sci. Med. Sci. 62 (2) (2009) 312–317.
[3] K.Z.H. Li, E. Roudaia, M. Lussier, L. Bherer, A. Leroux, P. McKinley, Benefits of cognitive dual-task training on balance performance in healthy older adults, J. Gerontol. Ser. A: Biol. Sci. Med. Sci. 65 (12) (2010) 1344–1352.
[4] L. Bherer, K.I. Erickson, T. Liu-Ambrose, A review of the effects of physical activity and exercise on cognitive and brain functions in older adults, J. Aging Res. (2013) 1–8.
[5] M. Agmon, B. Belza, H.Q. Nguyen, R.G. Logsdon, V.E. Kelly, A systematic review of interventions conducted in clinical or community settings to improve dual-task postural control in older adults, Clin. Intervent. Aging 9 (2014) 477–492.
[6] X. Zhu, S. Yin, M. Lang, R. He, J. Li, The more the better? A meta-analysis on effects of combined cognitive and physical intervention on cognition in healthy older adults, Ageing Res. Rev. 31 (2016) 67–79.
[7] M.K. Pichora-Fuller, S.E. Kramer, M.A. Eckert, B. Edwards, B.W. Hornsby, L.E. Humes, U. Lemke, T. Lunner, M. Matthen, C.L. Mackersie, G. Naylor, N.A. Phillips, M. Richter, M. Rudner, M.S. Sommers, K.L. Tremblay, A. Wingfield, Hearing impairment and cognitive energy: the framework for understanding effortful listening (FUEL), Ear Hear. 37 (1) (2016) 5–27.
[8] C.L. Baldwin, I.K. Ash, Impact of sensory acuity on auditory working memory span in young and older adults, Psychol. Aging 26 (1) (2011) 91–95.
[9] M. Woollacott, A. Shumway-Cook, Attention and the control of posture and gait: a review of an emerging area of research, Gait Posture 16 (2002) 1–14.
[10] B. Wollesen, K. Mattes, S. Schulz, L.L. Bischoff, L. Seydell, J.W. Bell, S.P. von Duvillard, Effects of dual-task management and resistance training on gait performance in older individuals: a randomized controlled trial, Front. Aging Neurosci. 9 (2017) 1–12.
[11] A. Shumway-Cook, M. Baldwin, N.L. Polissar, W. Gruber, Predicting the probability for falls in community-dwelling older adults, Phys. Ther. 77 (8) (1997) 812–819.
[12] H. Bruce, D. Aponte, N. St-Onge, N. Phillips, J.-P. Gagné, K.Z.H. Li, The effects of age and hearing loss on dual-task balance and listening, J. Gerontol.: Series B (2017).
[13] M. Agmon, L. Lavie, M. Doumas, The association between hearing loss, postural control, and mobility in older adults: A systematic review, J. Am. Acad. Audiol. 28 (6) (2017) 575–588.
[14] B. Wollesen, K. Scrivener, K. Soles, Y. Billy, A. Leung, F. Martin, N. Iconomou, C. McMahon, C. Dean, Dual-task walking performance in older persons with hearing impairment: Implications for interventions from a preliminary observational study, Ear Hearing 39 (2) (2017) 337–343.
[15] C. Lustig, P. Shah, R. Seidler, P.A. Reuter-Lorenz, Aging, training, and the brain: a review future directions, Neuropsychol. Rev. 19 (4) (2009) 504–522.
[16] D. Loewenstein, A. Acevedo, The relationship between instrumental activities of daily living and neuropsychological performance, in: T.D. Marcotte, I. Grant (Eds.), Neuropsychology of Everyday Functioning, The Guilford Press, New York, 2010, pp. 93–112.
[17] S.A. Fraser, K.Z.H. Li, N. Berryman, L. Desjardins-Crepeau, M. Lussier, K. Vadaga, L. Lehr, T.T.M. Vu, L. Bosquet, L. Bherer, Does combined physical and cognitive training improve dual-task balance and gait outcomes in sedentary older adults? Front. Hum. Neurosci. 10 (688) (2017) 1–12.
[18] P. Plummer, L.A. Zukowski, C. Giuliani, A.M. Hall, D. Zurakowski, Effects of

physical exercise interventions on gait-related dual-task interference in older adults: a systematic review and meta-analysis, Gerontology 62 (2015) 94–117.
[19] E.G.A. Karssemeijer, J.A. Aaronson, W.J. Bossers, T. Smits, M.G.M. Olde Rikkert, R.P.C. Kessels, Positive effects of combined cognitive and physical exercise training on cognitive function in older adults with mild cognitive impairment or dementia: A meta-analysis, Ageing Res. Rev. 40 (2017) 75–83.
[20] N. Theill, V. Schumacher, R. Adelsberger, M. Martin, L. Jäncke, Effects of simultaneously performed cognitive and physical training in older adults, BMC Neurosci. 14 (1) (2013) 103–117.
[21] K.Z.H. Li, U. Lindenberger, A.M. Freund, P.B. Baltes, Walking while memorizing: Age-related differences in compensatory behavior, Psychol. Sci. 12 (3) (2001) 230–237.
[22] R. Laatar, H. Kachouri, R. Borji, H. Rebai, S. Sahli, Combined physical-cognitive training enhances postural performances during daily life tasks in older adults, Exp. Gerontol. 107 (2018) 91–97.
[23] S.L. Tennstedt, F.W. Unverzagt, The ACTIVE study: study overview and major findings, J. Aging Health 25 (80) (2013) 3S-20S.
[24] B. Wollesen, C. Voelcker-Rehage, Training effects on motor–cognitive dual-task performance in older adults, Eur. Rev. Aging Phys. Activity 11 (1) (2013) 5–24.
[25] S.A. Fraser, K.Z.H. Li, N. Berryman, L. Desjardins-Crepeau, M. Lussier, K. Vadaga, L. Lehr, T.T.M. Vu, L. Bosquet, L. Bherer, Does combined physical and cognitive training improve dual-task balance and gait outcomes in sedentary older adults? Front. Hum. Neurosci. 10 (688) (2017) 1–12.
[26] Z.S. Nasreddine, N.A. Phillips, V. Bédirian, S. Charbonneau, V. Whitehead, I. Collin, J.L. Cummings, H. Chertkow, The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment, J. Am. Geriatr. Soc. 53 (4) (2005) 695–699.
[27] N.L. Jones, L. Makrides, C. Hitchcock, T. Chypchar, N. McCartney, Normal standards for an incremental progressive cycle ergometer test, Am. Rev. Respir. Dis. 131 (5) (1985) 700–708.
[28] D. Wechsler, Wechsler Adult Intelligence Scale: WAIS-IV Technical and Interpretive Manual, The Psychological Corporation, San Antonio, 2008.
[29] C. MacLeod, Half a century of research on the Stroop effect–An integrative review, Psychol. Bull. 109 (2) (1991) 163–203.
[30] S.L. Smith, K.M. Pichora-Fuller, K.L. Watts, C. La More, Development of the Listening Self-Efficacy Questionnaire (LSEQ), Int. J. Audiol. 50 (6) (2011) 417–425.
[31] L.E. Powell, A.M. Myers, The activities-specific balance confidence (ABC) scale, J. Gerontol. Series A: Biol. Sci. Med. Sci. 50 (1) (1995) 28–34.
[32] M. Lussier, C. Gagnon, L. Bherer, An investigation of response and stimulus modality transfer effects after dual-task training in younger and older adults, Training-induced Cognit. Neural Plast. 118 (6) (2016) 1–11.
[33] L. Lai, H. Bruce, L. Bherer, M. Lussier, K.Z.H. Li, Comparing the transfer effects of simultaneously and sequentially combined aerobic exercise and cognitive training in older adults, J. Cog. Enhancement. 1 (4) (2017) 478–490.
[34] M.L. Puthoff, Outcome measures in cardiopulmonary physical therapy: Short physical performance battery, Cardiopulmonary Phys. Ther. J. 19 (1) (2008).
[35] W.K. Kirchner, Age differences in short-term retention of rapidly changing information, J. Exp. Psychol. 55 (4) (1958) 352–358.
[36] L. Desjardins-Crépeau, N. Berryman, S.A. Fraser, T.T.M. Vu, M.-J. Kergoat, K.Z.H. Li, L. Bosquet, L. Bherer, Effects of combined physical and cognitive training on fitness and neuropsychological outcomes in healthy older adults, Clin. Interv. Aging. 11 (2016) 1287–1299.
[37] C. Strouwen, E.A.L.M. Molenaar, L. Munks, S.H.J. Keus, J.C.M. Zijlmans, W. Vandenberghe, B.R. Bloem, A. Nieuboer, Training dual tasks together or apart in Parkinson's disease: Results from the DUALITY trial, Movement Dis. 32 (8) (2017) 1201–1210.
[38] B. Godde, C. Voelcker-Rehage, Cognitive resources necessary for motor control in older adults are reduced by walking and coordination training, Front. Hum. Neurosci. 11 (156) (2017) 1–8.
[39] F. Barban, R. Annicchiarico, M. Melideo, A. Federici, M. Lombardi, S. Giuli, C. Ricci, F. Adriano, I. Griffini, M. Silvestri, M. Chiusso, S. Neglia, S. Ariño-Blasco, R. Cuevas Perez, Y. Dionyssiotis, G. Koumanakos, M. Kovačeić, N. Montero-Fernández, O. Pino, N. Boye, U. Cortés, C. Barrué, A. Cortés, P. Levene, S. Pantelopoulos, R. Rosso, J. Serra-Rexach, A. Sabatini, C. Caltagirone, Reducing fall risk with combined motor and cognitive training in elderly fallers, Brain Sci. 7 (19) (2017) 1–12.