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Walking to a Beat is Modulated by Task Complexity and Individual Differences in Age, Beat Perception, and Selective Attention

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Abstract

Increased walking variability is associated with risk of falling in older adults. Walking to a beat (Rhythmic Auditory Stimulation; RAS) can improve walking performance, however not all individuals benefit. Previous research shows that older adults show greater costs to performance compared to younger adults when performing a cognitive and a motor task simultaneously (i.e., dual tasking), particularly when the cognitive task is complex. The current study conceptualizes RAS as a dual-task situation (i.e., walking and synchronizing) with the aim of better understanding response (positive or negative) to RAS. We hypothesized that increasing task complexity would attenuate the benefit of RAS, particularly for older age groups. Young, middle-aged, and older adults performed walking as a single task and in three dual-task conditions: while synchronizing steps to low tones (*Simple*); to low and high tones (*Moderate*); to low and high tones while monitoring for a target sequence of tones (*Complex*). Middle-aged adults improved their walking in the *Simple* condition relative to walking in silence, but younger and older adults did not. This benefit was attenuated in the *Complex* condition. Stronger beat perception was associated with greater benefit to walking in the *Complex* condition. Stronger auditory selective attention was associated with greater benefit to walking in the *Moderate* condition. In conclusion, task complexity modulated response to RAS in middle-aged adults. Beat perception and selective auditory attention supported a positive response to RAS. Understanding when RAS benefits versus interferes with walking can help individuals optimize their environment to reduce risk of falls.

Keywords Rhythmic Auditory Stimulation · Dual-task · Aging · Cognition · Sensorimotor · Middle-Age

Introduction

Falls are a leading cause of injury and hospitalization among Canadian seniors (Public Health Agency of Canada, 2014). Increased gait variability is associated with increased risk for falls in older adults (Hamacher et al., 2011). To a greater extent than young adults, older adults rely on attentional resources to support consistent and stable walking (Yogev-Seligmann et al., 2008). Cognitive-motor interdependence occurs against the backdrop of age-related declines in attentional processes (Glisky, 2007). Thus, the ability of older adults to maintain stable walking increasingly depends on

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cognitive systems which are themselves undergoing age-related changes.

Rhythmic auditory stimulation (RAS), which involves walking to a metronome or to music with a steady beat, can improve gait among healthy older adults (Ghai et al., 2018). RAS has been shown to be superior to standard gait training among older adult inpatients in need of gait rehabilitation (Igusa et al., 2024). Music, as an instrument to deliver RAS, is a complex stimulus with various features that can be manipulated in any one study, and which may impact the effectiveness of RAS. For example, among healthy older adults the frequency (i.e., beats per minute) of the auditory stimulus should be set to equal to or slightly higher (10% faster) than the individual's normal walking cadence to effectively improve stride length and trunk sway (Minino et al., 2021). A salient rhythmic beat – like in high-groove music or a steady metronome – also appears to be an important feature of the auditory stimulus (Leow et al., 2021).

Further investigation of task-specific features of RAS and their impact on gait may be advanced by drawing from concepts from the field of cognitive-motor training. Previous research has demonstrated involvement of the prefrontal cortex during RAS, indicating attentional/executive function task demands (Vitorio et al., 2018). RAS can therefore be classified as a cognitive-motor task with both cognitive (i.e., attentional/perceptual) and motor (i.e., walking/synchronizing) demands. Cognitive-motor tasks can be further divided into those in which the cognitive task is independent (e.g., walking while counting backwards) versus integrated (e.g., dancing to music; Herold et al., 2018). Minimally, RAS involves walking while perceiving, attending, and synchronizing to a regular auditory pacing stimulus (e.g., music, metronome), and can be thought of as an integrated cognitive-motor task. However, there may be situations in which the cognitive demand of RAS pulls attentional resources away from the motor component, such as when walking to low-groove music (e.g., Ready et al., 2022), or possibly when attentional resources are divided between lyrical, melodical, rhythmical and other elements of music, leading to poorer outcomes. To investigate this possibility, it would be important to quantify motor as well as cognitive performance during RAS, as in dual-task paradigms (Plummer & Eskes, 2015).

The dual-task paradigm is an experimental design used to investigate the impact of simultaneous performance of a cognitive and motor task (Li et al., 2018). RAS is rarely investigated in a dual-task paradigm; however, this design can be useful in understanding the cognitive load associated with RAS. In one study, young and older adults showed longer probe reaction times during cued walking as compared to walking in silence, suggesting that walking to auditory cues is more attentionally demanding than walking in silence (Peper et al., 2012). Older adults show increased activation in the prefrontal cortex during single-task walking compared to young adults (Hoang et al., 2022). When walking performance is maintained, this upregulation is considered adaptive and is analogous to compensatory neural recruitment during cognitive tasks (Reuter-Lorenz & Park, 2023). As a result, cognitive-motor dual-tasking, particularly when the cognitive task is independent from the motor task, often results in greater costs among older adults compared to younger adults due to competition for cognitive capacity (Yogev-Seligmann et al., 2008). However, age-related differences in cognitive-motor dual-tasking may only be apparent when task demands are more challenging. For example, Lövdén and colleagues (2008) found that walking while performing a 1-back working memory task facilitated stride-time variability relative to walking in silence among young and older adults. This facilitation was attenuated in older adults at higher cognitive loads (e.g., 2-back, 3-back, 4-back conditions). Among young adults, however, dual-task walking was increasingly facilitated up to the 4-back condition. We know of no research which systematically varies different aspects of an auditory stimulus (e.g., variations in pitch) during RAS to investigate increasing task demands and their impact on gait among young and older adults. This type of experimental design, however, could prove useful in understanding the cognitive load of different elements of music during RAS and their impact on gait.

Importantly, individual differences impact response to RAS. Among older adults, metronome cues outperform music during RAS resulting in faster gait and longer strides, however, among young adults the opposite has been found (Roberts et al., 2021). Several studies have shown that healthy young and older adults who have stronger beat perception benefit more from RAS (e.g., Leow et al., 2014). Instructions to synchronize to a beat may be detrimental to poor beat perceivers, though may benefit good beat perceivers (Ready et al., 2019).

Auditory selective attention, the ability to attend to a target stimulus while filtering out irrelevant stimuli, may be an important individual difference factor which to our knowledge has not been investigated in the context of RAS. Music is a complex auditory stimulus and music listening involves processing and parsing out basic (e.g., pitch, temporal variation) and higher order (e.g., melody, rhythm) musical features (Särkämö & Sihvonen, 2018). Selective attention is recruited to perceive speech in noise (Oberfeld & Klöckner-Nowotny, 2016) and may be relevant for other complex auditory environments, such as music listening, as well. Attentive listening to music recruits fronto-parietal networks which serve domain-general attentional and working memory functions (Janata et al., 2002). Gait variability is associated with brain regions for higher order cognitive control (Tian et al., 2017) which may overlap with those of attentive listening. During RAS, individuals may vary in their ability to parse out and attend to beneficial information (i.e., a rhythmic beat) and to filter out less relevant information (e.g., melodic features or lyrical content).

The primary targets for RAS research have been healthy older adults (e.g., Minino et al., 2024), patients with movement disorders (e.g., Cochen De Cock et al., 2018), as well as young adults (e.g., Ready et al., 2019). Older adults have much to gain from interventions targeting the variability and stability of gait due to normative age-related changes in cognition and gait (Li et al., 2018). Data on gait changes in midlife are lacking (Herssens et al., 2018). In one study, walking speed was slower among middle-aged and older adults as compared to younger adults (Lindenberger et al., 2000), while in another study walking speed was stable in midlife and declined only in the 6th decade (Park et al., 2016). Regarding cognitive changes, longitudinal studies have shown gradual declines in processing speed and executive functioning in midlife (e.g., Hughes et al., 2018). As Lachman (2015) describes, middle-aged adults are underrepresented in the literature but are at a unique stage in the life course experiencing both some decline in cognitive and motor abilities but also some preserved capabilities. From the perspective of the current paper, midlife may represent a unique opportunity to implement RAS as a preventative intervention.

In summary, RAS has been studied among healthy young and older adults, as well as patients with movement disorders. Middle-aged adults, however, are an understudied but potentially important age group. Music is a complex stimulus, and different musical features (i.e., tempo, beat salience) and task instructions impact the effectiveness of RAS. To our knowledge there has been no systematic manipulation of task/musical complexity during RAS. It is known that individual differences in age and beat perception impact response to RAS, and individual differences in auditory selective attention may also be a factor.

To investigate these issues, we used a dual-task experimental design. Young, middle-aged, and older adults walked around an elliptical track in silence and while synchronizing their steps to a series of isochronous tones (i.e., a rhythmic beat). The complexity of the auditory stimulus was manipulated by varying pitch and cognitive load. This allowed us to examine gait variability under increasing levels of complexity of the auditory stimulus. Performance on the Words-In-Noise task (WIN; an ecologically valid task requiring auditory selective attention) and the Beat Alignment Task (BAT) were assessed to clarify any heterogeneity in response to dual-task conditions. We hypothesized that 1) walking to a simple beat would result in decreased gait variability as compared to walking in silence; 2) as the complexity of the auditory stimulus increased, gait variability should increase, particularly for middle-aged and older adults; 3) those with better beat perception would benefit more from walking to a beat as compared to those with poorer beat perception; 4) those with better auditory selective attention would benefit more from walking to a beat as compared to those with poorer auditory selective attention.

Method

Participants

Young adults (18—35 years, $n=27$) were recruited from the university psychology participant pool. Middle-aged (50—60 years, $n=22$) and older adults (61—85 years, $n=32$) were recruited via existing contact lists and from flyers distributed on campus and on social media. Young adults received course credit for participating in this study whereas middle-aged and older adults received an honorarium. Inclusion criteria included fluency in English, ability to walk without assistive devices, absence of neurological, cardiovascular, orthopedic, and musculoskeletal conditions that affect mobility or cognition, absence of a diagnosed hearing impairment or uncorrected visual impairment. We did not include any criteria regarding level of musical training or musical background. Data for five young adults (excluded = 1, dropped out = 2, data loss = 2), two middle-aged adults (did not meet inclusion criteria = 1, dropped out = 1), and 12 older adults (excluded = 8, dropped out = 4) were not included in the present study. Reasons for exclusion included having a pure tone average (PTA) threshold > 25 dB HL in the better ear, which would indicate mild hearing loss (World Health Organization, 1991). Reasons for dropping out included preference to not participate in in-person activities during the COVID-19 pandemic, illness/injury occurring outside of the study, and time constraints. Data from a total of 22 young adults, 20 middle-aged adults, and 20 older adults were included in the present analyses. Participants were cognitively healthy and had normal hearing (see Table 1). A power analysis based on pilot data using a generalized linear model (Lakens & Caldwell, 2021) with effect size of $f=0.2$ (considered small to medium; Cohen, 1992) and alpha-level of $\alpha=0.5$ suggested that 20 participants per age group would achieve a power of at least .80 for most effects, which is similar to previous studies (Huxhold et al., 2006; Lövdén et al., 2008). We recruited participants until a sample size of at least 20 participants per group was reached. Linear mixed effects modeling was chosen to minimize bias and increase statistical power given our relatively small sample size (McNeish & Harring, 2017).

Table 1 Participant Characteristics M (SD) for Young, Middle-Aged, and Older Adults

Variable	YA (n=22)	MA (n=20)	OA (n=20)	*p*	η^2_G / X^2
Age (years)	23.32 (3.30)$^{\$+}$	54.95 (2.95)$^{*\$}$	69.95 (4.90)$^{*+}$	<.001	.97
Number (percent) women	17 (77%)	14 (70%)	12 (60%)	.41	4.0
MoCA total (/30)	27.86 (1.64)	26.65 (1.81)	27.20 (2.02)	.11	.07
PTA threshold (HL) in better ear	1.08 (4.11)$^{+\$}$	5.75 (4.58)$^{*\$}$	10.63 (5.43)$^{*+}$	<.001	.42
Words in Noise total (/35)	23.70 (1.75)$^{\$}$	23.18 (1.71)	22.25 (1.85)*	.03	.11
Trails B—A (sec.)	29.36 (10.07)$^{\$}$	32.41 (12.66)	39.93 (14.32)*	.02	.12
Single-task step-time CoV%	3.73 (1.42)	3.77 (1.24)	3.82 (1.27)	.97	.00
Cadence	108.82 (8.95)	109.20 (5.90)	107.70 (7.96)	.82	.01
Timed Up and Go (sec.)	7.92 (1.17)$^{\$}$	8.64 (0.87)	9.29 (1.91)*	.01	.15
Beat Alignment Task (/24)	21.95 (2.98)	20.95 (3.03)	20.40 (3.30)	.26	.04
Geriatric Depression Scale (/30)	7.41 (4.89)$^{\$}$	5.55 (3.99)	4.11 (3.41)*	.05	.10
Auditory monitoring task (/10)	5.55 (6.79)	2.14 (4.99)	0.05 (8.59)	.06	.13

Note. YA=young adults, MA=middle-aged adults, OA=older adults, CoV=Coefficient of Variation. * indicates statistically significant difference relative to YA $^{+}$ indicates statistically significant difference relative to MA $^{\$}$ indicates statistically significant difference relative to OA

Materials and Procedure

Participants completed two in-person sessions on separate days, each lasting 2 – 2.5 h. The first session consisted of assessments of physical/mental health, auditory, motor, cognitive functioning, and beat perception. The measures reported on in the current manuscript are described in detail below. For details of other measures administered during session 1 see *Online Resource 1*. The second session consisted of the experimental protocol.

Session 1: Screening and Background

Middle-aged and older adults were pre-screened via telephone to determine eligibility. Informed consent was obtained for young adults and eligible middle-aged and older adults.

Physical and Mental Health Participants completed an intake questionnaire measuring physical health. The Geriatric Depression Scale (GDS) was administered to assess for depression with values>9 indicating mild depression (Sheikh & Yesavage, 1986). The GDS has shown strong classification accuracy in young and middle-aged adults (Guerin et al., 2018).

Auditory Functioning Auditory acuity was measured using a Maico (MA 42) audiometer. Pure-tone audiometric thresholds were measured at frequencies from 250 to 8000 Hz in both ears following standard procedure. A PTA was derived by averaging detection thresholds at 500, 1000, 2000, and 4000 Hz, in the better ear. The Words-in-Noise Test (WIN; Wilson et al., 2003) was used to assess auditory selective attention. Participants repeated words out loud which were presented against multi-talker babble at different signal-to noise ratios via headphones. The outcome is number of words correct.

Mobility, Cognition, and Beat Perception The Timed Up and Go (TUG; Podsiadlo & Richardson, 1991) task was used as an index of general mobility. Participants had to stand up from a chair, walk 3 m, turn around, walk back and return to sitting. Time (s) to complete the task is measured. The MoCA was used as a global measure of cognition (Nasreddine et al., 2005) with a score of 26 or greater /30 indicating normal cognition. Executive functioning was measured with the Trail Making Test (TMT; Reitan, 1958) which measures visuomotor processing speed (Trails A) and switching (Trails B). A switching cost was calculated (Trails B—A). Beat perception was measured with a short version of the Beat Alignment Task (BAT), a subtest from the Battery for the Assessment of Auditory and Timing Abilities (BAASTA; Dalla Bella et al., 2017a). Participants listened to computer-generated fragments of well-known music and indicated whether a superimposed isochronous sequence was aligned with the beat of the music or not. The outcome is total number correct.

Session 2: Experimental Tasks

We used the dual-task design in which a listening task and a walking task were first performed separately then simultaneously. The order of single-task conditions (i.e., walking and listening) and the order of dual-task conditions (i.e., *Simple*, *Moderate*, *Complex*) was counterbalanced.

Single-Task Listening The auditory stimuli consisted of pure tones presented in an isochronous rhythm. The rate of tones was 10% faster than preferred cadence, as this has been shown to benefit gait (Minino et al., 2021). Preferred cadence (steps per minute) was determined at the beginning of the second session by measuring the number of steps taken at a comfortable walking speed in 10 s and multiplying by 6. The tones were either low (750 Hz) or high (1500 Hz). To equate for audibility, the volume of the auditory stimuli was adjusted individually to be 50 dB SPL higher than each participant's PTA threshold, determined in Session 1. Tones were generated in MATLAB (MATLAB, 2018) and were presented via bluetooth using Avantree wireless over-the-ear headphones.

The listening task had three conditions representing increasing levels of complexity. In the *Simple* condition participants heard low tones. In the *Moderate* condition participants heard low and high tones with a ratio of 65:35 of low:high tones. For both conditions, participants were instructed to sit with their eyes open and listen to the tones. Thus, there is an increase in complexity of the nature of the auditory stimulus from the *Simple* to the *Moderate* conditions. In the *Complex* condition participants heard low and high tones and additionally completed an auditory monitoring task in which they responded via a manual clicker, as quickly and as accurately as possible, when they heard a particular pattern of tones. Specifically, the target sequence was: "high, low, high, low." Two distractor sequences were also presented: "high, low, low, high," and "high, low, high, high." Each block consisted of 10 target sequences and 10 of each distractor sequence with a low tone separating each sequence, in a random order. The outcome measure was the number of correctly identified targets minus the number of responses unrelated to targets (i.e., hits—false alarms). Thus, the *Moderate* and the *Complex* conditions have identical stimuli. The instruction to monitor for a particular pattern of tones in the *Complex* condition was designed to increase cognitive load relative to the *Moderate* condition. Each trial consisted of 198 tones. For the single-task conditions, the *Complex* condition consisted of two trials while the *Simple* and *Moderate* conditions consisted of one trial to decrease testing burden.

Single-Task Walking Participants walked in an elliptical circuit in silence for two minutes. Older adults on average take 107 steps per minute (Brown et al., 2014). Two minutes was chosen to ensure the collection of at least 50 gait cycles, following recommendations by König and colleagues (2014). Participants were instructed to walk at a comfortable speed. Participants completed two trials, in a clockwise and then counterclockwise direction. The ellipse was 2.2 m wide and 9.07 m long and the perimeter of the ellipse was indicated with blue blocks. Step-times were measured using Noraxon DTS Foot Switches, which are pressure sensitive sensors, attached to the heel and toe of the participant's footwear (Noraxon, 2013). The foot switches recorded time stamps and therefore capture temporal but not spatial data.

Dual-Task Conditions In the dual-task conditions participants walked the elliptical track while performing each of the three listening task conditions. They were asked to synchronize their walking to the tones. Each dual-task condition was performed once in a clockwise and once in a counterclockwise direction. During pilot testing participants found it difficult to complete the *Complex* dual task without completing the *Complex* single task first. Therefore, the *Complex* single task was always presented immediately before and immediately after the *Complex* dual task, regardless of the order of dual-task conditions.

Data Analyses

Walking data were pre-processed using a custom-developed Python script. Outliers were defined as scores with an absolute z-score > 2.5 and were Winsorized within their respective age group. Each outcome measure grouped by age group and condition had an absolute skew index below 3 and an absolute kurtosis value below 10 and so were considered not severely non-normal (Kline, 2020). Missing data included one missing value (1.6%) for the Geriatric Depression Scale due to experimenter error, and 17 participants (27.4%) had missing data for the auditory monitoring task due to equipment failure. At the time of the equipment failure the young adult group was nearly complete, resulting in more missing data for middle-aged and older age groups (1 younger adult, 8 middle-aged adults, and 8 older adults). The differences between age groups are therefore an artifact of our recruitment schedule rather than having to do with age per se. These data were considered missing completely at random and were excluded in a pairwise fashion following guidelines by Kang (2013).

The primary outcome measure was dual-task cost (DTC) of step-time coefficient of variation (CoV) % (step-time CoV% = standard deviation / mean * 100), where $DTC_{CoV} = (\text{dual-task}_{CoV} - \text{single-task}_{CoV})/\text{single-task}_{CoV} * 100$. A DTC score of zero is equal to walking performance during single-task walking and a score below 0 indicates facilitated (i.e., less variable) walking relative to single-task walking. Therefore, DTC step-time CoV% means were tested against a null hypothesis of zero to determine if walking variability under dual-task conditions was statistically significantly different from walking variability during single-task walking. The secondary outcome measure was performance on the *Complex* condition of the listening task, where the outcome measure was hits minus false alarms.

All statistical analyses were performed in R (R Core Team, 2021). To investigate our hypotheses, we applied linear mixed effects analyses to the data using lmerTest (Kuznetsova et al., 2017) with lme4 (Bates et al., 2015). Outcome variables were not severely non-normal nor heteroscedastic; more details can be found in the *Online Resource 2*. For both models, to facilitate interpretation, continuous variables were mean-centered. Two separate linear mixed effects models were constructed for each of the two outcome variables. To avoid overfitting, likelihood ratio tests were used to obtain AIC and *p*-values to determine if adding predictors statistically significantly added to model fit, beginning with a random intercept model. Only models in which additional predictors statistically significantly improved model fit were retained, otherwise they were rejected. More information on model selection can be found in *Online Resource 2*. For the first model examining walking performance, participants and walking direction nested within participants were added as random effects. Dual-task condition, age group, beat alignment score, and performance on the Words-in-Noise task were added as fixed effects. For the second model examining performance on the auditory monitoring task participants were added as a random effect. Fixed effects were age group and performance on the MoCA. Other variables were considered but not retained in the final models, see *Online Resource 2* for further details. Omnibus *F* and *p* values were calculated using the car R package (Fox & Weisberg, 2011) and using Kenward-Roger's method to estimate degrees of freedom (Halekoh & Højsgaard, 2014). When a statistically significant interaction effect was detected the emmeans R package (Lenth, 2020) was used to test post-hoc comparisons using the Bonferroni adjustment for multiple comparisons (where 3 or more comparisons were made). Following recommendations by Lorah (2018), f^2 was calculated as an overall effect size of each model, where 0.02, 0.15, and 0.35 are considered small, medium, and large effects respectively. Standardized β coefficients were calculated to indicate the magnitude of effects with larger values indicating a greater effect. β coefficients are not always comparable between studies, particularly with smaller sample sizes. A 10% change in gait variability has been shown to predict injurious falls (Verghese et al., 2009). To better contextualize the walking performance data within the wider literature, a change of > 10% was used as a benchmark for a practically significant change in gait variability as measured by step-time CoV%. Figure plots were generated using the sjPlot R package (Lüdecke, 2023).

Table 2 Step-time CoV% for Each Walking Condition for Young, Middle-Aged, and Older Adults

Age Group	ST walking (n = 62)	DT Simple (n = 62)	DT Moderate (n = 62)	DT Complex (n = 62)
Young adults (n = 22)	3.73 (1.42)	3.56 (1.46)	3.55 (1.35)	3.37 (1.72)
Middle aged adults (n = 20)	3.77 (1.24)	3.29 (1.96)	2.87 (0.95)	3.37 (1.55)
Older adults (n = 20)	3.82 (1.27)	3.62 (1.32)	3.64 (1.75)	3.80 (2.06)

ST = single task, DT = dual task

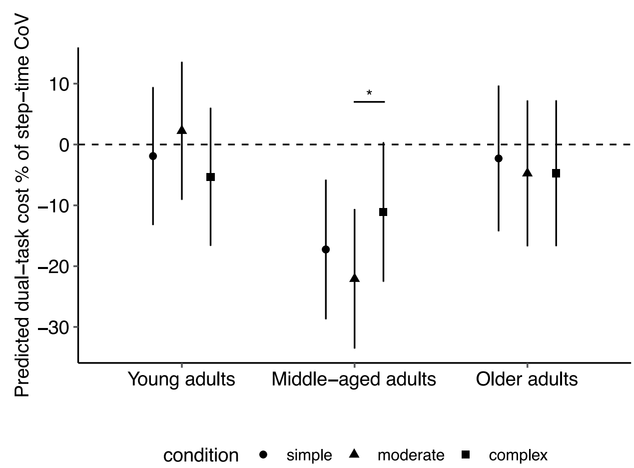

Fig. 1 Dual-task cost% in step-time CoV by age group and condition. Middle-aged adults were overall facilitated under dual-task conditions, and this facilitation was attenuated in the dual-task *Complex* condition. Young and older adults were not facilitated in any condition. Error bars are 95% confidence intervals of the estimated marginal means

Results

Raw step-time CoV% values for each condition and age group are presented in Table 2.

Model 1: DTC of Step-Time CoV%

The overall effect size for model 1 was f^2 = 0.10. There was a statistically significant interaction between condition and age group [F (4, 238) = 2.71, p = 0.031], see Fig. 1. There was no main effect for condition [F (2, 238) = 1.72, p = .181], and no main effect of age group [F (2, 81.35) = 2.29, p = .108]. Post-hoc comparisons showed that among middle-aged adults walking was more variable in the dual-task *Complex* compared to the dual-task *Moderate* condition (β = 0.59, *SE* = 0.18). For middle-aged adults, DTC scores were statistically significantly lower than zero during the dual-task *Simple* (DTC CoV = -17.25%, p = 0.004) and *Moderate* (DTC CoV = -22.09%, p < 0.001) conditions, but not the *Complex* condition (DTC CoV = -11.09%, p = 0.061). In contrast, DTC scores for young and older adults were not statistically significantly different from zero in any dual-task condition and were not statistically significantly different between conditions (*p*s > .05). This result partially supports hypothesis 1, that walking to a simple beat will result in decreased gait variability as compared to walking in silence; and partially supports hypothesis 2, that increasing attentional load will be associated with increasing gait variability (i.e., decreased benefit), particularly for older age groups.

There was a statistically significant interaction between condition and beat perception score [F (2, 238) = 4.99, p = .008], see Fig. 2, and no main effect of beat perception score [F (1, 81.35) = 0.19, p = .667]. The association between beat perception and DTC step-time CoV% was statistically significantly more negative in the dual-task *Complex* compared to the dual-task *Simple* condition (β = -0.24, SE = 0.08). This result supports hypothesis 3, that those with greater beat perception will benefit more from cued walking.

There was a statistically significant interaction between condition and performance on the Words-in-Noise task [F (2, 238) = 4.51, p = .012], see Fig. 3, and no main effect of performance on the Words-in-Noise task [F (1, 81.35) = 0.004, p = .948]. The association between performance on the Words-in-Noise task and DTC step-time CoV% was statistically significantly more negative in the dual-task *Moderate* compared to the dual-task *Simple* condition (β = -0.22, SE = 0.08). This result supports hypothesis 4, that those with greater selective auditory attention will benefit more from cued walking.

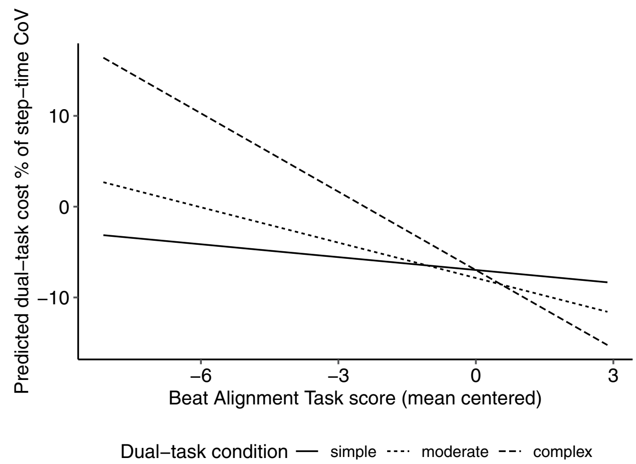

Fig. 2 The association between higher score on the Beat Alignment Task and lower DTC in step-time CoV% (i.e., less variable walking) was strongest during dual-task *Complex* condition

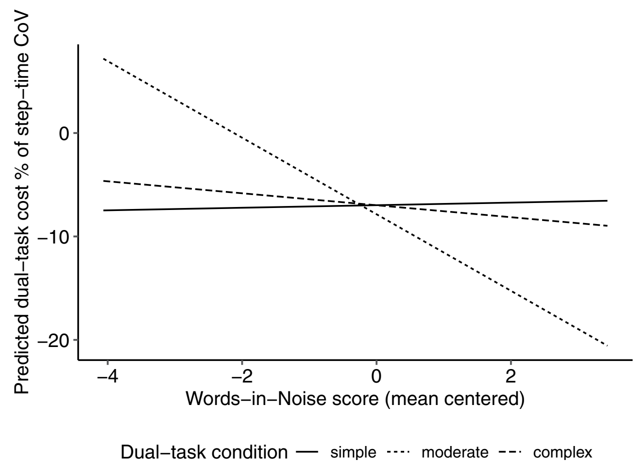

Fig. 3 The association between higher performance on the Words-in-Noise task (i.e., better auditory selective attention) and lower DTC in step-time CoV% (i.e., less variable walking) was strongest during the dual-task *Moderate* condition

Model 2: Hits Minus False Alarms

The overall effect size for model 2 was f^2 = 0.21. There was a statistically significant main effect of MoCA score [F (2, 41.13) = 4.68, p = 0.036], such that those with a higher MoCA score performed better on the auditory monitoring task (β = 0.28, SE = 0.13). The main effect of Age Group was not statistically significant [F (2, 41.07) = 2.97, p = .062]. As described above, 17 participants (1 younger adult, 8 middle-aged adults, and 8 older adults) had missing data for auditory monitoring task due to equipment failure.

Post-Hoc Analyses

Our first hypothesis was that walking to a simple beat will result in decreased gait variability as compared to walking in silence. This effect was observed for middle-aged but not older adults. Follow-up analyses were conducted to explain the null finding among older adults. In the *Simple* condition, older adults' DTC score ranged from – 59% to 72%. Correlations showed that older adults with slower TUG time to completion had lower (i.e., facilitated) DTC step-time CoV% (r = -0.41, p = .009). Similarly, older adults with higher single-task step-time CoV% had lower DTC step-time CoV% (r = -0.36, p = .022). Further correlations were conducted to investigate possible trade-offs between cognitive and motor performance in the dual-task *Complex* condition. DTC step-time CoV% was not statistically significantly correlated with hits minus false alarms in this condition (r = -0.008, p = 0.939).

Discussion

In this study we conceptualized RAS as an example of a dual-task situation (i.e., walking while simultaneously synchronizing footsteps to a beat). Our objective in using this theoretical approach was to investigate the attentional demands of RAS, and the impact of increasing complexity of an auditory pacing stimulus on gait variability. We also adopted a lifespan perspective and included young, middle-aged, and older adults in our sample to better characterize changes in response to RAS with aging. The main findings of this study are as follows. First, RAS benefitted step-time variability among healthy middle-aged adults and a subset of older adults. Second, the benefit seen in middle-aged adults was attenuated when task demands were more complex. Finally, those who had stronger beat perception and selective auditory attention had better walking performance under conditions of increased task complexity.

Middle-Aged Adults Benefit from Walking to a Beat

In partial support of our first hypothesis, walking to a simple auditory cueing stimulus resulted in decreased step-time CoV% compared to walking in silence for middle-aged adults. Stride time CoV% can discriminate fallers and non-fallers (Hausdorff et al., 1997), highlighting the functional significance of these results. Previous research has indicated that a 10% increase in gait variability predicts future falls (Verghese et al., 2009). Walking during auditory stimulation resulted in a decrease in step-time CoV% greater than 10% in this study and therefore was a practically significant reduction in gait variability.

Previous research has shown that the use of assistive devices during walking requires cognitive resources (Wright & Kemp, 1992). Whether or not to use an assistive device involves a cost–benefit analysis (Li et al., 2001). When the cognitive load associated with using an assistive device is negligible, older adults freely use the device to improve their walking. If the costs of using the device are too high, then the individual may not use it. Under our task conditions, the cost–benefit analysis of using an auditory cueing stimulus to improve walking was favorable for middle-aged adults and, as our post-hoc analyses revealed, for a subset of older adults.

Middle-aged adults may represent a "goldilocks" group due to their unique cognitive-motor profile. Middle-aged adults show some age-related decline in cognitive (Gunstad et al., 2006) and motor (Park et al., 2016) performance. However, they may have greater reserve capacity to navigate cognitive-motor dual-tasking compared to older adults. In one study, middle-aged adults showed smaller DTCs as compared to older adults, despite similar baseline walking speed in both groups (Lindenberger et al., 2000). Midlife may be an ideal period for preventative interventions such as RAS to mitigate declines in motor performance and reduce risk for falls later in life. This age group has a tipping point as well, however, as demonstrated by the attenuation of benefit in the *Complex* condition in our study (see discussion below).

Contrary to our prediction, at the group level older adults did not improve their gait variability when walking to an auditory beat. Given this unexpected finding follow-up analyses were undertaken. These revealed that in the *Simple* condition, older adults with poorer baseline motor performance benefitted more than those with better baseline motor performance. This is consistent with previous research showing that patients with Parkinson's Disease who have poorer motor performance at baseline have the most to gain from RAS (Dalla Bella et al., 2017b). On the other hand, a subset of older adults in our study did not benefit in the *Simple* condition. Previous research has shown that healthy older adults can accrue a cost to walking performance during RAS (Hamacher et al., 2016). This cost has been attributed to the instruction to synchronize steps to tones, which may induce an internal focus of attention to the detriment of gait (Wulf, 2013). Older adults in our study who showed a DTC during the *Simple* condition had better baseline motor performance and may have been more susceptible to this effect.

Among young adults, step-time CoV was less variable in the *Complex* condition as compared to any other condition (see Table 2). Though this was not statistically significant, this echoes research showing that the addition of a low cognitive load can improve walking (Lövdén et al., 2008). The cognitive load in our study may have been too low to produce a statistically significant benefit to walking among younger adults in the *Simple* condition. Alternatively, young adults may have already been at ceiling in terms of their walking performance.

One limitation of our study is the use of a single index to measure gait variability. Step-time CoV% was chosen for its functional significance as stride-time CoV% has been shown to discriminate fallers and non-fallers (Hausdorff et al., 1997) and has been shown to predict falls (Hausdorff et al., 2001) among older adults. We therefore consider step-time CoV% to be an appropriate measure of gait variability in initial investigations of the impact of increasing task complexity in the context of RAS. A related limitation is that we were unable to directly measure gait speed, which is related to gait variability (Jordan et al., 2007). Cadence did not differ between age groups (see Table 1) and did not explain variance in step-time CoV% in this study (see *Online Resource 2*). It is possible, however, that the increase in gait variability among middle-aged adults with increasing complexity of the listening task is confounded by a decrease in gait speed. We could not investigate this directly and this is a limitation of the current study. Future studies can extend our findings by including multiple indices of gait variability and including a measure of gait speed in the context of increasing task demands during RAS.

Benefit to Gait During RAS Was Modulated by Task Complexity

Numerous experimental studies have shown that walking performance decreases with the addition of a secondary cognitive task, particularly among older adults (Yogev-Seligmann et al., 2008). Older adults show increased involvement of frontal resources during single-task walking as compared to young adults, leaving fewer resources available to navigate cognitive-motor dual-task conditions (Li et al., 2018) in keeping with studies of cognitive aging (Reuter-Lorenz & Park, 2023). We proposed that, like previous findings using experimental designs involving both a cognitive and motor task (e.g., Lövdén et al., 2008), increasing attentional load during RAS would result in decreased gait consistency and that this effect would be more pronounced among older age groups. This hypothesis was partially supported as only middle-aged adults benefited from the cueing stimulus in the *Simple* condition and showed the expected decrease in benefit to gait with increased task complexity. Previous research has shown that RAS is attentionally demanding for healthy young and older adults (Peper et al., 2012). Our study extends this finding to middle-aged adults and additionally indicates that when the demands of RAS exceed resource capacity there ceases to be a benefit.

Conceptually, the cognitive demands of RAS can be considered on a continuum from integrated to independent from the motor demands (Herold et al., 2018). Our findings suggest that where task demands fall on this continuum has consequences for the effectiveness of RAS in benefitting gait. In our *Simple* condition the cognitive and motor tasks are integrated (i.e., listening to and synchronizing to the tones) and in this condition we see a benefit to gait in middle-aged adults. When the cognitive task demands move towards being independent from the motor task, as in the *Complex* condition (i.e., walking while monitoring for a target sequence of tones), the benefit to gait is attenuated. This theoretical framework can be useful in guiding clinicians when developing treatment protocols for their patients: the more integrated the cognitive and motor demands of RAS, the more likely there will be a benefit to gait.

Unlike middle-aged adults, older adults did not show the expected decrease in walking performance with increasing task complexity. Nor did we detect differences in the auditory monitoring task between single- and dual-task conditions, though due to limitations of this task this should be considered a conservative estimate. There was a substantial amount of missing data for the listening task. The loss of data was due to equipment failure and not likely due to systematic bias. The data loss may have led to low power which may explain the null dual-task effects. There was a wide range of scores on the auditory monitoring task, see Table 1. For those who performed more poorly, floor effects may have obscured dual-task interference effects. Those with higher general cognition (i.e., higher MoCA scores) showed better performance on the auditory monitoring task and may have been able to successfully navigate task demands under dual-task conditions due to higher cognitive capacity. Post-hoc analyses indicated that dual-task walking and dual-task auditory monitoring task performance were not correlated, suggesting the absence of cognitive-motor trade-offs. Due to the limitations of the auditory monitoring task described above, our results should be interpreted cautiously.

Individual Differences in Beat Perception

Healthy adults with poor beat perception are less likely to benefit from RAS (Leow et al., 2014). We extended these findings by showing that adults with poorer beat perception were less likely to benefit from RAS under more complex task conditions. Researchers have previously proposed that those with poorer beat perception have the additional cognitive load of extracting the beat from music during RAS (Ready et al., 2022). In the *Complex* condition of our study, participants were required to continuously attend to a series of tones, and to hold in their mind and update the sequence of the previous four tones to detect the target sequence. This suggests that updating/working memory may be a relevant cognitive ability for using an auditory stimulus to benefit one's walking. Grahn and McAuley (2009) proposed that strong beat perceivers rely on implicit beat perception whereas weak beat perceivers explicitly compare timing intervals to extract a beat. In our study, explicitly extracting the beat from the auditory stimulus may have used up available working memory resources, leaving weak beat perceivers unable to meet the working memory demands of the *Complex* condition. Individuals with reduced cognitive resources and poor beat perception may be susceptible to this effect at even lower task demands, as has been previously demonstrated (Cochen De Cock et al., 2018). In our study, better beat perception did not confer an advantage when walking to a simple auditory beat, in contrast to previous studies (e.g., Leow et al., 2014). Participants in our study had high scores on the BAT, see Table 1, indicating that they were good beat perceivers. The restricted range of scores in our study may have led to Type II statistical error. A broader range of scores may have revealed an advantage for better beat perceivers in the *Simple* and *Moderate* conditions as well.

Individual Differences in Auditory Selective Attention

Those with better performance on the Words-in-Noise task were better able to use the auditory cues to benefit their walking in the dual-task *Moderate* condition. The Words-in-Noise task measures the ability to recognize words in the presence of multi-talker babble (Wilson et al., 2003). The ability to report on task-relevant stimuli and filter out task-irrelevant stimuli is supported by auditory selective attention. A similar auditory selective attention demand may be involved in our *Moderate* dual-task condition. The *Moderate* condition consisted of low and high tones, with the instruction to synchronize to all the tones in the same way, and no instruction to attend to the changes in pitch. Those with poorer auditory selective attention may have been less able to ignore the changes in pitch (an irrelevant feature of the auditory stimuli in terms of improving gait consistency) and to attend to the rhythmic aspect of the tones to benefit their walking. On a practical level, our results suggest that those with poorer auditory selective attention may be less able use more complex musical stimuli (e.g., with intricate melodic lines, harmonies, syncopated rhythms, etc.) to benefit their walking during RAS. Clinicians may want to select music for RAS which directs attention towards the musical beat.

Conclusion

In conclusion, the present study conceptualizes RAS as an example of a dual-task situation. Considered from this perspective our results suggest that benefitting from RAS requires attentional resources, and that increased task complexity leads to an attenuation in benefit via dual-task interference. These results suggest that the complexity of the musical elements contained within the auditory stimulus presented during RAS may play a role in the efficacy of RAS. The ability of any individual to handle the cognitive load inherent in RAS may depend on their age, beat perception ability, and selective attention capacity. Which cognitive processes are most important depends on task demands, characterized by the auditory scene. Given their unique cognitive-motor profile, middle-aged adults may be well-positioned to benefit from RAS interventions to improve gait and mitigate age-related changes in walking consistency.

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Data availability Data will be made available on request.

Declarations

Competing Interest Simone Dalla Bella is on the board of the BeatHealth company dedicated to the design and commercialization of technological tools for assessing rhythm capacities (e.g. BAASTA) and implementing rhythm-based interventions.

Ethical Approval This project involves human participants and has received approval from the University Human Research Ethics Committee of Concordia University.

Informed Consent Informed consent was obtained from participants prior to participating in this study.

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