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RESEARCH

Tuned to walk: cue type, beat perception, and gait dynamics during rhythmic stimulation in aging

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Abstract

Rhythmic auditory cueing (RAC) improves spatiotemporal gait parameters in older adults, often using isochronous rhythmic cues (i.e., with constant inter-beat-intervals). However, healthy gait contains fractal-like variability, (i.e., with persistent long-range correlations; LRC) which is disturbed when walking to isochronous cues. Embedding auditory cues with a fractal structure increases LRC in gait among young and older adults, though middle-aged adults are under researched. Walking requires greater cognitive resources with increased age, though how different cue-types interact with attentional load during RAC is under researched. This may depend on beat perception, as those with better beat perception benefit more from RAC. The aim of this study was to investigate the optimal parameters for RAC across the adult lifespan. We predicted that 1) walking to fractal cues would increase LRC in gait across the adult lifespan; 2) increasing attentional load would decrease LRC in gait, particularly for older adults. Moderating effects of beat perception on the impact of cue-type on LRC were also explored. Young, middle-aged, and older adults (n = 62) walked around an elliptical track in silence and in three cued walking conditions of increasing attentional load. Tones were presented in isochronous and fractal rhythms. Fractal cues increased LRC in gait, with qualitatively greater increase among middle-aged adults. Attentional load had no effect on LRC in gait. Isochronous cues resulted in decreased LRC in gait, particularly for those with better beat perception. The optimal parameters of RAC therefore depend on age, beat perception, and the target gait parameter.

Keywords Rhythmic auditory cueing · Dual task · Fractal · Beat perception · Aging · Attention

Introduction

Walking to external auditory cues, termed rhythmic auditory cueing (RAC), is an intervention for gait rehabilitation which improves spatiotemporal gait parameters in healthy older adults (Ghai et al. 2018). However, previous studies investigating RAC have rarely considered the temporal structure of gait, which is fractal-like in nature and consists of long-range correlations, in conjunction with attentional load. While it is known that walking increasingly relies on

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attentional resources with increased age (Yogev-Seligman et al., 2008), relatively little is known about how attentional load impacts the long-range correlations in gait across the adult lifespan during RAC. Additionally, auditory cues which are embedded with a fractal temporal structure are superior to isochronous cues (i.e., with a constant inter-beat interval) in preserving the long-range correlations in gait (Dotov et al. 2017). How this effect may manifest among those with better or poorer beat perception is not known, though this may be an important factor given that those with better beat perception are more likely to benefit from RAC (Cochen de Cock et al. 2018). Across research investigating RAC to improve gait in aging, samples of middle-aged adults are lacking. Therefore, the current study aims to investigate the impact of cue-type and attentional load on the long-range correlations in gait and whether these are moderated by individual differences in age and beat perception.

Age-related changes in the temporal structure of gait

Healthy gait contains some variability which is non-random and possesses fractal properties which means that it has a predictable structure over time (Goldberger et al. 2002). Fractal patterns are characterized by persistent long-range correlations, meaning that each stride interval is correlated with previous stride intervals. The fractal scaling exponent (α) describes the persistence of long-range correlations in a time series (Quixadá et al. 2022). In a persistent time series (i.e., $0.5 > \alpha < 1.0$), large values tend to be followed by large values, and small values by small values. In an anti-persistent time series (i.e., $\alpha < 0.5$), large values tend to be followed by small values and vice versa. Observations in a time series may also be uncorrelated (i.e., random; $\alpha = 0.5$). Healthy gait typically shows a fractal scaling exponent (α) between 0.8 and 1.0 consistent with persistent long-range correlations, with values closer to 0.5 or above 1.0 considered deviations from the healthy state (Goldberger, 2002). Long-range correlations in gait are less persistent among older adults as compared to young adults (Hausdorff 2007), and among older adults with a history of falls (Herman et al. 2005). The temporal structure of gait and whether it possesses persistent long-range correlations is therefore clinically relevant and is the main outcome of interest in the current study. A handful of studies have reported a fractal scaling exponent (α) of 0.80 (Terrier and Dériaz 2012) and 0.73 (Homs et al. 2022) among middle-aged adults at preferred walking speed. However, more research is needed to fully describe the temporal structure in gait among middle-aged adults.

The temporal structure of auditory cues during RAC

Walking to regular auditory cues is an empirically supported intervention for gait rehabilitation among healthy older adults (Ghai et al. 2018). Many studies investigating RAC use an auditory stimulus with an isochronous temporal structure (e.g., Minino et al. 2021). However, walking to isochronous auditory cues has the unfortunate effect of reducing α values, making stride-to-stride gait fluctuations more random, as has been demonstrated in patients with Parkinson's Disease and healthy age-matched controls (Dotov et al. 2017). In one study, healthy middle-aged adults showed anti-persistent long-range correlations in gait when synchronizing to isochronous auditory cues during treadmill walking (Terrier and Dériaz 2012). Less commonly, researchers have studied the impact of embedding beat sequences with fluctuations containing fractal patterning (i.e., which mimic those of healthy gait patterns) on long-range correlations in gait. Young adults can adapt the correlational structure of their walking to match that of the auditory pacing stimulus (Marmelat et al. 2014). Older adults with Parkinson's Disease and healthy older adults show more persistent stride-to-stride variations (i.e., higher α values) when walking to a fractal metronome than when walking in silence (Marmelat et al. 2020). There is a lack of studies investigating middle-aged adults. Taken together these studies show that isochronous cues, which are commonly used in RAC, disrupt the long-range correlations of healthy gait. Embedding a metronome with a fractal temporal structure, on the other hand, can improve the long-range correlations in gait. The impact of cue-type on the long-range correlations of gait among middle-aged adults is not well-described.

The role of attention during cued walking

Along with changes to gait, individuals experience normative cognitive decline with increased age. Older adults experience decreases in grey matter volume and white matter integrity, and these brain changes are associated with performance declines in tests of executive and attentional functioning (Park and Reuter-Lorenz 2009). Changes to cognitive and motor systems in aging do not occur in a vacuum but rather interact such that they compete for common attentional and executive function resources (Li et al. 2018). In other words, cognitive and motor systems are interdependent and increasingly so with increased age (Yogev-Seligmann et al. 2008). Cognitive-motor interactions have been investigated with the dual-task design in which a motor task and a cognitive task are performed separately, then simultaneously (Li et al. 2018). Generally, the addition of a cognitive task results in poorer performance, called dual-task costs (Yogev-Seligmann et al. 2008).

The literature is mixed as to the impact of adding a secondary cognitive task on the temporal structure of gait. Among healthy young adults, no change in α values were observed while concurrently performing a working memory task (e.g., Grubaugh and Rhea 2014). In another study, young adults showed decreased in α values while texting answers to arithmetic calculations performed mentally relative to walking in silence (e.g., Grabiner et al. 2018). Differences in task difficulty may account for discrepant findings. In one study, older adults showed less persistent long-range correlations in gait while concurrently performing a letter fluency task relative to walking in silence (Lamoth et al. 2011). Previous studies have shown that while both cognitive-motor and rhythm-motor dual-tasks (such as RAC) require attentional resources, rhythm-motor dual-tasking may support a more favourable gait pattern (Kim et al. 2017). However, experimental designs combining rhythmic cueing during cognitive-motor dual-tasking are needed to determine if and how rhythmic cues moderate dual-task performance.

There is a dearth of research investigating the impact of attentional load on the long-range correlations of gait during RAC. More generally, diverting attention away from auditory stimulation by adding an unrelated cognitive task results in slower and shorter strides among young adults, suggesting that benefitting from auditory stimulation requires attentional resources (Leow et al. 2018). Additionally, healthy young and older adult controls can use rhythmic cues with the instruction to take bigger steps to improve dual-task gait velocity and stride length relative to uncued dual-task walking (Lohnes and Earhart 2011). This suggests that rhythmic stimulation can reduce dual-task interference effects. In another study, RAC increased gait variability relative to walking in silence among healthy older adults (Hamacher et al. 2016). This deleterious effect on gait was reversed with the addition of an unrelated cognitive task. The negative effect of RAC on gait variability was attributed to the induction of an internal focus of control, which can disrupt automatic control processes in gait (Wulf 2013). Adding a cognitive load in this case released the internal focus, thereby reducing gait variability.

In summary, gait requires increased attentional resources with increased age. The small body of literature investigating the impact of attentional load on the long-range correlations in gait indicate that these are sensitive to dual-task costs, though potentially only under conditions of high task complexity. RAC may moderate the relationship between walking performance and attentional load. Empirical work investigating manipulations of attentional load during RAC and considering the temporal structure in gait is lacking.

Individual differences in response to RAC

There is evidence that individuals vary in their response to RAC and studying these individual differences can further our understanding of the mechanisms of RAC. Those with better beat perception and who are better able to synchronize their steps to rhythmic cues benefit more in terms of gait speed from cued walking (Cochen De Cock et al. 2018). Consistent with these findings, researchers have proposed that benefit to gait during RAC is mediated by a domain-general timing system responsible for perceptual (e.g., beat perception) and motor (e.g., sensorimotor synchronization) timing abilities (Puyjarinet et al. 2019). Other researchers have further proposed that synchronizing steps to tones represents an additional cognitive load for poor beat perceivers which can result in a negative response to RAC (see Ready et al. 2022). Consistent with this, we have shown that poor beat perceivers are particularly disadvantaged under conditions of high cognitive load during cued walking (Parker et al. 2025). The above studies did not investigate long-range correlations in gait, and it therefore remains unclear whether beat perception moderates the effect of RAC on this parameter. In addition, the auditory stimuli in the above studies were limited to isochronous metronome cues or music. It is not known whether beat perception ability moderates gait performance under fractal auditory cueing conditions. The current study therefore aims to explore whether beat perception moderates the effect of isochronous and fractal auditory cues on the long-range correlations in gait.

Current study

The overarching goal of this study is to better understand the optimal parameters of RAC with three specific aims. The first aim is to investigate age-related differences in the effect of synchronizing to isochronous versus fractal auditory cues on the long-range correlations in gait across the adult lifespan. The second aim is to examine the role of attention during RAC by manipulating attentional load during cued walking and observing the impact on long-range correlations in gait. The third aim is to examine whether individual differences in beat perception interact with cue-type during RAC. To address these goals, we asked young, middle-aged, and older adults to walk around an elliptical track while synchronizing their steps to auditory cues that varied in their temporal structure and attentional load. The change in fractal characteristics of walking from a walking in silence baseline were then compared between conditions. We predicted that 1) walking to fractal cues would increase the fractal scaling exponent (α) relative to walking to isochronous cues for all age groups; 2) increasing attentional load would decrease the fractal scaling exponent (α), particularly for older adults. It remains an open question whether beat perception ability moderates the effect of cue-type on the temporal structure of gait. We therefore explored potential moderating effects of beat perception ability without making a directional prediction.

Method

Participants

Participants and further details on the protocol have been described more fully elsewhere (Parker et al. 2025). Eligibility was determined via online survey (young adults) or telephone screening (middle-aged and older adults). Informed consent was obtained from eligible participants. The final sample consisted of 22 healthy young, 20 middle-aged, and 20 older adults recruited from Concordia University's Psychology participant pool (young adults), and from existing contact lists, flyers distributed on campus, and social media (middle-aged and older adults). Young adults received course credit for their participation, and middle-aged and older adults received an honorarium. All age groups were cognitively healthy (i.e., Montreal Cognitive Assessment score > 23; Carson et al. 2018), had hearing within the normal range (i.e., Pure Tone Average (PTA) < 25 dB HL derived by averaging pure-tone detection threshold at 500, 1000, 2000, and 4000 Hz in the better ear; World Health Organization 1991), and were not depressed (i.e., score on the Geriatric Depression Scale < 10; Sheikh and Yesavage 1986), see Table 1. This project received approval from the University Human Research Ethics Committee of Concordia University.

Table 1 M *(SD) for participant characteristics*

Variable	Young adults $n=22$	Middle-aged adults $n=20$	Older adults $n=20$	p	η^2_G
Age in years	23.32 (3.26)	54.95 (2.91)	69.95 (4.84)	<.01	.97
Number (%) women	17 (77%)	14 (70%)	12 (60%)	.09	
Montreal Cognitive Assessment (/30)	27.86 (1.62)	26.65 (1.79)	27.20 (1.99)	.11	.07
Pure-tone average threshold (HL)	1.08 (4.06)[b,c]	5.75 (4.52)[a,c]	10.63 (5.36)[a,b]	<.01	.42
Geriatric Depression Scale (/30)	7.41 (4.83)[b,c]	5.55 (3.94)	4.11 (3.37)	.05	.10
Beat Alignment Test (/24)	21.95 (2.95)	20.95 (3.00)	20.40 (3.26)	.26	.04

[a]statistically significantly different from young adults; [b] statistically significantly different from middle-aged adults; [c] statistically significantly different from older adults

Procedure

In the first session participants completed background assessments and questionnaires. Participants completed the experimental tasks in a second session on a different day. Both sessions had a duration of approximately 2–2.5 h.

Background assessment

Participants completed the Montreal Cognitive Assessment which is a screening measure for cognitive impairment, where scores < 26/30 indicate possible cognitive impairment (Nasreddine et al. 2005). The original cut-score has been shown to overestimate cognitive impairment, particularly among older adults and those with lower education, while a cut-score of < 23/30 leads to a lower false positive rate (Carson et al. 2018). The less stringent cut-score of < 23/30 was therefore used in this study. Cognition has been associated with both hearing health and depression. Participants were therefore screened for hearing impairment with pure-tone audiometry testing using a standard staircase testing procedure (Schlauch and Nelson 2015). A PTA was calculated by averaging the quietest sound (dB HL) that a participant could detect across 500, 1000, 2000, 4000 Hz in the better ear. Participants were excluded if they had a PTA > 25 dB HL (World Health Organization 1991). Participants also completed the Geriatric Depression Scale (GDS; Sheikh and Yesavage 1986), a self-report questionnaire which screens for depression and is appropriate for use in older adults, as well as in young and middle-aged adults (Guerin et al. 2018). A score > 10 indicates mild depression. To measure beat perception, participants completed a short version of the Beat Alignment Test (BAT; Iversen and Patel 2008), a subtest from the Battery for the Assessment of Auditory and Sensorimotor Timing Abilities (BAASTA; Dalla Bella et al. 2017, 2024), in which they heard musical excerpts with a metronome superimposed on top of the music. Participants were asked to identify whether the metronome was aligned, or not aligned, with the beat of the music. The short version of the BAT used in this study has a maximum of 24, with higher scores indicating better beat perception.

Experimental tasks

Auditory conditions

Three auditory conditions of increasing attentional load were performed in a seated position. Participants were instructed to listen to the tones with their eyes open. In the first condition participants listened to a series of low tones (750 Hz); in the second, participants listened to a series of low (750 Hz) and high tones (1500 Hz); in the third, participants listened to low and high tones while performing an auditory task in which they monitored for a target sequence of tones (High, Low, High, Low). For the auditory monitoring task participants were instructed to respond as quickly and as accurately as possible via a manual clicker when they detected the target sequence. The outcome measure for the auditory monitoring task was hits minus false alarms.

Tones were presented via Bluetooth to Avantree wireless over-the-ear headphones worn by the participants, and were generated in MATLAB (MathWorks 2018). Volume was individually adjusted to be 50 dB SPL higher than the participant's PTA SPL. The rate of tones was set to 10% faster than the participant's preferred walking speed, which was assessed prior to beginning the experimental tasks. During the seated auditory tasks, the first two auditory conditions were presented with isochronous cues only to reduce participant burden. The third condition was presented with both isochronous and fractal cues, with two trials for each cue type. For the fractal cues, the coefficient of variation (i.e., magnitude of variability) around the mean inter-beat interval was set to 2%, as in previous research (Dotov et al. 2017). The Hurst exponent (H) was set to $H = 0.85$, corresponding to very persistent fluctuations characteristic of human gait. Perfectly persistent fluctuations of fractal dynamics or $1/f$ pink noise is characterized by $H = 1.0$ (Stadnitski 2012).

Uncued walking

Participants walked around an elliptical track (approximately 4 m wide and 9 m long) at their preferred walking speed. Participants were instructed to walk at a natural and comfortable speed. 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).

Cued walking conditions

Participants walked around the elliptical track and were instructed to synchronize their steps to the tones of each of the three auditory conditions described above. Cues in each auditory condition were presented in both an isochronous and in a fractal rhythm, resulting six cued walking conditions (3 auditory conditions × 2 cue types). Each condition was completed twice, once while walking in a clockwise and once in a counter-clockwise direction. Order of conditions was counterbalanced.

Analyses

Walking data were pre-processed using a custom-developed Python script. For the walking data, no outliers were detected when defined as scores with an absolute z-score > 3. Background variables showed large variability, particularly among older adults. When outliers were defined as having an absolute z-score > 3, extreme scores were not captured as they distorted the mean. Thus, for all other data, outliers were defined as having an absolute z-score > 2.5 and were Winsorized within their respective age group. Each outcome measure grouped by age group, cue type, and condition had a skew index below an absolute value of 3 and a kurtosis value below an absolute value of 10 and so were considered not severely non-normal (Kline 2020). Data was complete for all variables except for 1 missing value (1.6%) for the Geriatric Depression Scale due to experimenter error. Seventeen participants (27.4%) had missing data for the auditory monitoring task due to equipment failure. At the time of the equipment failure middle-aged and older adults were being recruited, resulting in more missing data for these age groups (1 younger adult, 8 middle-aged adults, and 8 older adults). These data were considered missing completely at random and were excluded in a pairwise fashion following guidelines by Kang (2013).

Two main outcome measures were investigated. The first outcome measure was the fractal scaling exponent (α), which describes the strength of long-range correlations present in gait. We used Detrended Fluctuation Analyses (DFA) to estimate the fractal exponent (Likens 2022). Computations were performed in MATLAB. DFA as applied to the analysis of gait has been described in detail elsewhere (Damouras et al. 2010). Briefly, a time series is first integrated and divided into windows or box sizes of length n. Within each window, a regression line is fit to and then subtracted from the data (i.e., the data are detrended). Next, the average fluctuation of the integrated and detrended time series $F(n)$ is determined by taking the root mean square of the residuals in each scale. This calculation is repeated over range of different window sizes. The fractal scaling exponent (α) is estimated as the slope of the regression line to the log–log graph of $F(n)$ and n. Following recommendations for shorter time series (Phinyomark et al. 2020), we implemented an overlapping window methodology to calculate the scaling exponent (α) using window sizes from 10 to a maximum of the time series length divided by eight (Almeida et al. 2013). For the main analyses, the fractal scaling exponent (α) was converted into change score ($change_{\alpha} = cued_{\alpha} - uncued_{\alpha}$), such that a positive change score represented an increase in the fractal scaling exponent (α) towards more persistent long-range correlations. This outcome measure was chosen as our research questions involve predicting change in the fractal scaling exponent (α) during cued relative to uncued walking. The second outcome measure was performance on the auditory monitoring task, where the outcome 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). Two separate linear mixed effects models were constructed for each of the two main outcome variables: change in fractal scaling exponent (α) and hits minus false alarms. 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. Participants and direction (clockwise versus counterclockwise) nested within participants were added as random effects. The fixed effects examined were Auditory Condition, Cue Type, Age Group, Beat Perception, and Uncued Fractal Scaling Exponent (α). Uncued Fractal Scaling Exponent (α) was included as a measure of individual motor functioning. To facilitate interpretation continuous variables were mean-centered. Interactions between fixed effects were also considered in model selection. More detail on model selection and investigations of the dependent variables can be found in the Supplementary Information. The final models are as follows:

$$ChangeinFractalScalingExponent\,(\alpha) \sim CueType * (AgeGroup + BeatPerception) + UncuedFractalScalingExponent\,(\alpha) + (1|ID) + (1|WalkingDirection : ID)$$

$$HitsMinusFalseAlarms \sim AttentionalLoad * AgeGroup + (1|ID)$$

Omnibus *F* and *p* values were calculated using the car R package (Fox and Weisberg 2011) and using Kenward-Roger's method to estimate degrees of freedom (Halekoh and 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. Plots were generated using the sjPlot R package (Lüdecke 2023).

Results

Raw mean values of the fractal scaling exponent (α) across conditions and cue type are reported in Table 2.

Change in fractal scaling exponent (α)

There was a statistically significant Cue Type by Age Group interaction, $F(2, 616.00) = 8.59$, $p < 0.001$, see Fig. 1, with a main effect of Cue Type, $F(1, 616.00) = 45.63$, $p < 0.001$, and no main effect of Age Group, $F(2, 76.03) = 2.11$, $p = 0.13$. Post-hoc tests were performed against the null hypothesis of 0, representing no change from uncued walking. All age groups showed increases in the fractal scaling exponent (α) while walking to fractal cues relative to uncued walking (*p*s < 0.05). This increase was qualitatively greater among middle-aged adults ($m = 0.18$) compared to older ($m = 0.10$) and young ($m = 0.10$) adults, although age groups were not statistically significantly different. Further, a decrease in the fractal scaling exponent (α) was observed when walking to isochronous cues relative to uncued walking among middle-aged ($m = -0.09$, $p = 0.01$) and older adults ($m = -0.15$, $p < 0.001$), but not young adults ($m = -0.05$, $p = 0.15$). These result supports our first prediction, that walking to fractal cues would increase the fractal scaling exponent (α) for all age groups.

Auditory Condition did not statistically significantly improve model fit and therefore was not included in the final model. This is described in the Supplementary Information in more detail. Our second prediction, that increasing attentional load would result in a decrease in the fractal scaling exponent (α), particularly for older adults, was therefore not supported.

There was a main effect of Beat Perception, $F(1, 72.01) = 13.74$, $p < 0.001$, and a statistically significant interaction between Beat Perception and Cue Type, $F(1, 616.00) = 35.37$, $p < 0.001$, see Fig. 2. Post-hoc tests were performed against a null hypothesis of 0, representing no change from uncued walking. When walking to isochronous cues, higher beat perception scores were associated with a decrease in the fractal scaling exponent (α) ($B = -0.024$, $SE = 0.007$, $p < 0.001$). The slope of the association between beat perception and change in the fractal scaling exponent (α) was not statistically significantly different from zero under the fractal condition ($B = 0.001$, $SE = 0.007$, $p = 0.87$). Thus, better beat perception was associated with less persistent long-range correlations in gait when walking to isochronous, but not fractal, cues.

There was a main effect of Uncued Fractal Scaling Exponent (α), $F(1, 101.97) = 97.12$, $p < 0.001$, such that a lower Uncued Fractal Scaling Exponent (α) values at baseline

Table 2 Mean values of the fractal scaling exponent (α) across conditions and cue type for each age group

Age group	Uncued	Isochronous cues			Fractal cues		
		LT	LT and HT	LT and HT + task	LT	LT and HT	LT and HT + task
Young adults $n = 22$	0.75	0.66	0.63	0.63	0.79	0.82	0.82
Middle-aged adults $n = 20$	0.58	0.58	0.53	0.62	0.82	0.89	0.82
Older adults $n = 20$	0.75	0.62	0.56	0.56	0.83	0.84	0.75

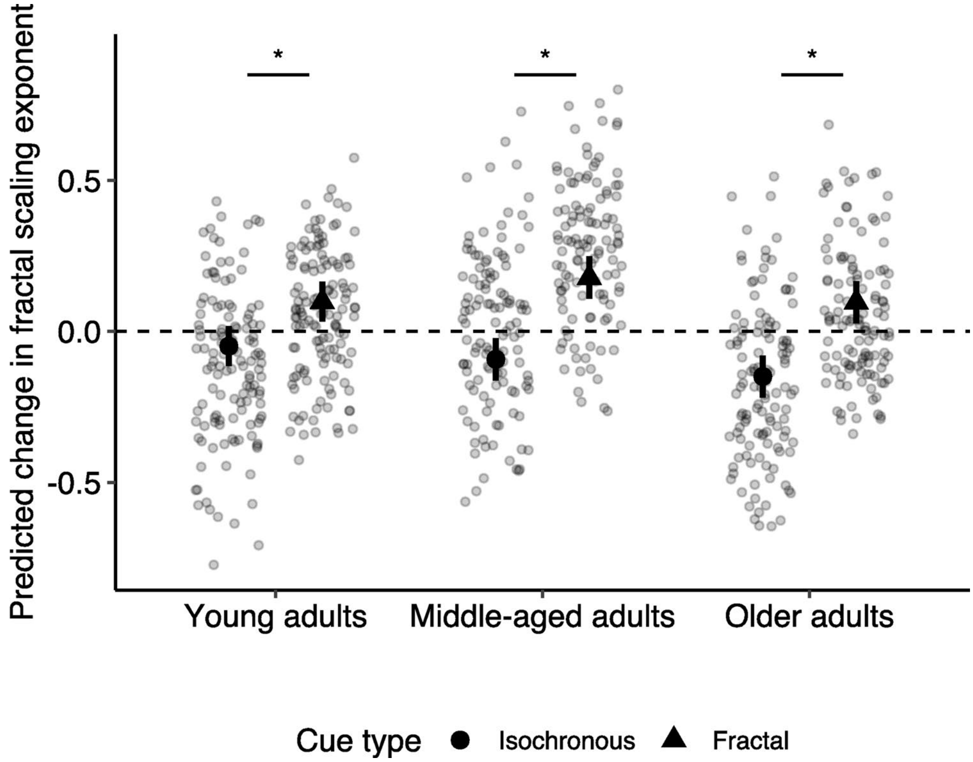

Fig. 1 Estimated change in the fractal scaling exponent (α) by cue type and age group. Walking to fractal cues resulted in a higher fractal scaling exponent relative to walking to isochronous cues, particularly for middle-aged adults. Estimated marginal means are displayed as large shapes, error bars are 95% confidence intervals of the estimated marginal means. Raw data is overlayed

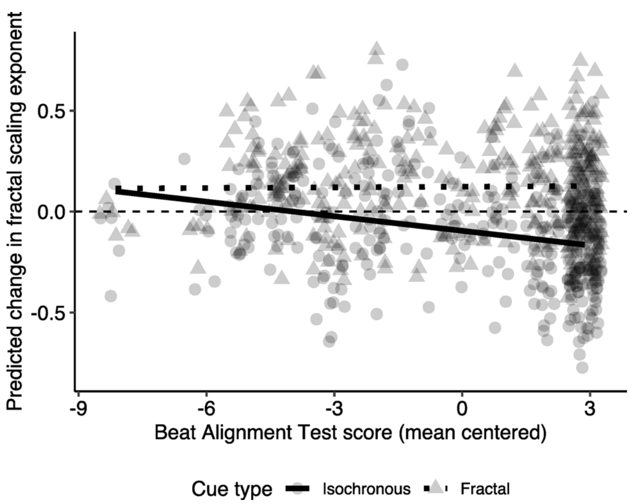

Fig. 2 Change in the fractal scaling exponent (α) by cue type and beat perception. Increasing beat perception score was associated with decreasing fractal scaling exponent (α) while walking to isochronous cues (solid line). No relation was observed when walking to fractal cues (dotted line). Raw α values under isochronous (circles) and fractal (triangles) cueing conditions has been overlayed

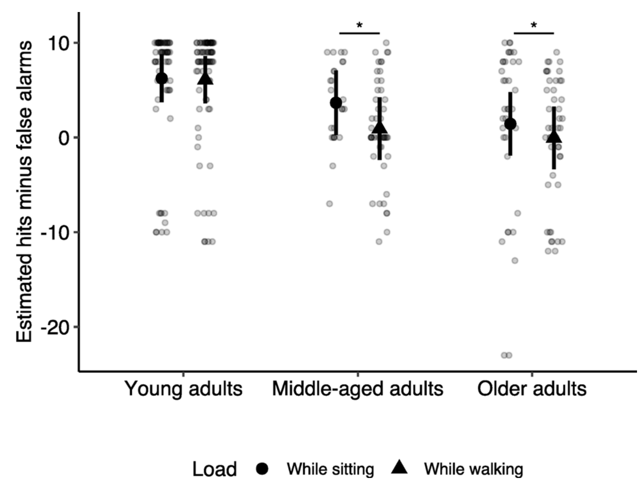

Fig. 3 Performance on the auditory monitoring task by attentional load and age group**.** Middle-aged adults and older adults showed a cost to performance in the auditory monitoring task while walking compared to while sitting. Young adults maintained task performance across conditions of attentional load. Estimated marginal means are displayed as large shapes, error bars are 95% confidence intervals of the estimated marginal means. Raw data is overlayed

(i.e., less persistent long-range correlations in gait) was associated with an increase in fractal scaling exponent (α) during cued walking (B = −0.755, SE = 0.077).

Hits minus false alarms

There was a statistically significant Attentional Load by Age Group interaction, $F(2, 256.38) = 4.06$, $p = 0.02$, see Fig. 3, with no main effect of Attentional Load, $F(1, 256.62) = 0.07$, $p = 0.79$, nor of Age Group, $F(2, 48.39) = 2.64$, $p = 0.08$. Post-hoc contrasts showed that middle-aged and older adults performed significantly worse on the auditory monitoring task while walking compared to while sitting ($m_{\text{diffMA}}=-2.73$, $p<0.001$; $m_{\text{diffOA}}=-1.48$, $p=0.03$), while young adults showed no costs to monitoring performance when walking compared to sitting ($m_{\text{diffYA}}=0.14$, $p=0.79$).

Discussion

The main goal of this study was to better understand the effects of fractal patterning of auditory cues, attention, and individual differences in rhythm perception on the efficacy of RAC in older and middle-aged adults. We investigated the impact of these factors on the temporal structure of gait during RAC by manipulating attentional load and cue type in a dual-task design. The main findings of this study are as follows: first, walking to fractal cues resulted in increased α values relative to uncued walking in healthy adults across the lifespan. This increase was qualitatively greater among middle-aged adults compared to other age groups. Second, attentional load did not alter the temporal structure of gait. Third, better beat perception was associated with a decrease in α values when walking to isochronous cues.

Fractal cues improved the temporal structure in gait

In line with our prediction and consistent with previous literature with individuals with Parkinson's Disease (Dotov et al. 2017), fractal cues resulted in increased α values, signifying more persistent long-range correlations in gait, while isochronous cues resulted in decreased α values. We extended previous findings by demonstrating these effects in healthy middle-aged adults, in addition to healthy older adults. Taken in the context of the wider literature, the benefit to spatiotemporal parameters of gait observed when walking to isochronous cues (e.g., Minino et al. 2021), may come at the cost of a more random temporal structure of gait.

Less persistent long-range correlations in gait are observed among older adults and people with neurodegeneration (Ravi et al. 2020), and among older adults with a history of falls (Herman et al. 2005). Asymmetries in long-range correlations between legs also predicts falls prospectively among healthy older adult women (Paterson et al. 2011). And, more persistent long-range correlations in gait are associated with better gait adaptability among young adults (Ducharme et al 2018). These studies are in line with previous assertions that long-range correlations are a potential marker of falls risk (Hausdorff 2007). Importantly, the clinical and functional implications of inducing more persistent long-range correlations in gait via RAC is not well-understood. Previous researchers have demonstrated carry-over effects from RAC, suggesting that RAC does not simply act as an external pacemaker but at least temporarily restores naturalistic gait patterns (Rhea et al. 2014). However, future studies are needed to investigate whether inducing persistent long-range correlations in gait via rhythmic stimulation produces clinically meaningful outcomes, such as reduced falls risk.

Age-related differences in response to RAC

In our study, all age groups showed an increase in α values towards more persistent long-range correlations in gait when walking to fractal auditory cues as compared to walking in silence. Further, the magnitude of this increase was greatest among middle-aged adults. While this finding was not statistically significant, we argue that it is practically significant. The α values of middle-aged adults during uncued walking were much lower than either young or older adults (see Table 2). When walking to auditory fractal cues, α values of all age groups converged to be increasingly fractal-like with α values of 0.79, 0.82, and 0.83 for young, middle-aged, and older adults, respectively. These values reflect natural variability characteristic of a healthy system (Hausdorff 2009). This dovetails with our finding that lower α values during uncued walking were associated with greater increases in α values during cued walking. These results suggest the motor profile of the individual impacts their response to RAC. This is consistent with previous research (Marmelat et al. 2020) and is clinically relevant, suggesting that individuals with poorer motor functioning have the most to gain from RAC with a fractal patterning.

Middle-aged adults have often been excluded from research in aging (Lachman 2015). The inclusion of this age group is therefore a novel aspect of this study. When they are included, middle-aged adults tend to fall in between young and older adults in terms of their cognitive (Schaie 2005) and motor performance (Park et al. 2016). Dual-task costs among middle-aged adults can resemble those of younger or older adults, depending on the outcome measured (Lindenberger et al. 2000). Previous studies have reported α values of 0.73 (Homs et al. 2022) and 0.80 (Terrier and Dériaz 2012) for middle-aged adults when walking on a treadmill at their preferred walking speed. The middle-aged adults in our sample were significantly older than in previous studies, with a mean age of 54 years old, and we used overground walking. It is unknown whether individuals in this age range have lower α values, or whether this is specific to our sample and methodology. Further research with a larger sample is needed to quantify the gait dynamics of middle-aged adults. If our results are replicated, then middle-aged adults could be a target for interventions to prevent or mitigate age-related changes in walking.

Notably, in our study the mean α values during uncued walking for both young and older adults were 0.75. Generally, fractal dynamics in gait are known to break down with aging with young adults showing α values closer to 0.85 and older adults showing values of 0.75 (Kobsar et al. 2014). However, some researchers have proposed α values close to 0.75 represents an optimal balance between stability and adaptability (Rhea and Kiefer 2014). Another consideration is that the limited number of steps collected in this study may have produced biased estimates. In our study, trials were approximately 2 min in length, while previous studies have used trials of 10 min in length (e.g., Kobsar et al. 2014), producing significantly more steps. While we have followed methodological recommendations for shorter time series (Phinyomark et al. 2020) this remains a limitation of our study. We would therefore interpret observed α values cautiously. Additionally, older adults in our study may have been higher in functioning, which may explain the similar α values between young and older adults. Individual studies report a wide range of α values for older adults as low as 0.64 (Dotov et al. 2017) and as high as 0.85 (Kaipust et al. 2013). This suggests a wide range of interindividual variability which may be due to lifestyle factors (Franklin and Tate 2009). Older adults in our study were recruited from flyers posted at a community gym and may be more likely to be physically active and cognitively healthy relative to peers of the same age who do not regularly exercise. In support of this view, older adults in this study showed few differences in terms of measures of cognitive, mental, (see Table 1) and physical (see Table 2) health relative to younger adults.

Attentional load did not impact fractal dynamics in gait during RAC

Contrary to our prediction, increasing the attentional load during RAC did not alter the temporal structure of gait. It is well-established that many aspects of walking rely on attentional and executive function resources. Numerous studies have shown that walking performance decreases with the addition of a secondary cognitive task (Yogev-Seligmann et al. 2008) and that similar neural circuits are engaged by both cognitive and motor tasks (Li et al. 2018). The role of attention during cued walking is less well-understood. We proposed that increasing attentional load would disrupt the temporal structure in gait and that this effect would be more pronounced among older age groups, consistent with previous research of cognitive-motor dual-tasking (Li et al. 2018). Contrary to our prediction, long-range correlations in gait were not impacted by attentional load in our study. However, our results are generally consistent with the assertion that there would be increased dual-task interference during RAC with increased age, as evidenced by the cost to performance on the auditory monitoring task among middle-aged and older adults, but not younger adults.

Middle-aged and older adults may have prioritized gait performance over performance on the cognitive task in our study, a possibility acknowledged by Peterson and Smulders (2015). Young adults in our study may have had enough attentional capacity to maintain task performance under dual-task conditions, as evidenced by the overall high scores of young adults on the auditory monitoring task under single- and dual-task conditions. Older adults tend to prioritize the more ecologically valid task of walking to ensure safety while sacrificing performance on a cognitive task (Yogev-Seligmann et al. 2012). The instruction to "synchronize your steps to the tones" in our study may have led middle-aged and older adults to prioritize performance on the walking task over the cognitive task. In this way, walking performance may have been maintained despite cross-competition for common attentional resources between the walking and the auditory tasks. The finding that middle-aged and older adults performed more poorly on the auditory monitoring task when walking compared to while sitting (see Fig. 3) supports this conclusion.

Another possibility is that adapting the correlational structure of one's gait to match that of a cueing stimulus does not require attentional resources. While previous studies have found no dual-task effect in either the correlational structure of gait or in the performance of a concurrently performed working memory task (Grubaugh and Rhea 2014), several other studies have found evidence of dual-task interference. In one study walking while performing serial-7 subtractions, but not serial-3 subtractions, resulted in decreased α values for adults with Parkinson's Disease (see Hausdorff 2009). Cognitive tasks involving executive functioning (Tanimoto et al. 2016) or highly attention-demanding tasks (Grabiner et al. 2018) have resulted in decreases in α values during dual-tasking among healthy young adults. These studies suggest that an unrelated secondary task can disrupt the temporal structure of gait under conditions of high cognitive load. However, these studies did not include an auditory pacing stimulus. A handful of studies have examined the impact of adding an unrelated cognitive task during cued walking and have found evidence of dual-task interference, suggesting that cued walking is attentionally demanding (e.g., Peper et al. 2012). However, these studies did not examine the impact on long-range correlations in gait.

Our study fills an important gap by investigating the impact of attentional load during cued walking on long-range correlations in gait. Whether or not gait dynamics are impacted by attentional load has clinical relevance. For example, clinicians may be advised to construct RAC interventions with minimal cognitive load to avoid interference effects.

Beat perception exaggerated the response to RAC

We did not find an association between beat perception scores and long-range correlations when walking to fractal auditory cues. Previous studies showing an advantage for good beat perceivers regarding spatiotemporal gait parameters have reported bimodally distributed beat perception scores (Ready et al. 2019) and a median score of 68% (Roberts et al. 2021). Our inability to detect an effect under the fractal cueing condition may be related to differences in the distribution of beat perception scores in our sample. In our sample, the modal value of the BAT was 24/24, suggesting that our sample consisted primarily of good beat perceivers. A ceiling effect may therefore have led to type II statistical error.

When walking to isochronous cues, better beat perceivers in our study had *reduced* α values, meaning less persistent long-range correlations in gait. At first glance this result seems at odds with previous literature indicating that better beat perceivers are more likely to show a positive response to RAC (Cochen de Cock et al. 2018). However, these studies have not considered long-range correlations in gait. Previous research has shown that isochronous cues degrade long-range correlations found in healthy gait (Dotov et al. 2017). We have extended these findings by further showing that those with better beat perception were more prone to this effect. To our knowledge, ours is the first study to examine how walking to isochronous auditory cues impacts the temporal structure of gait for those with better or worse beat perception. While immediately counterintuitive, our finding is logical when considering the nature of healthy gait versus that of an isochronous stimulus. Healthy gait is characterized by variability in stride-to-stride intervals which is fractal-like in its temporal structure. In contrast, isochronous cues are invariant. It is unsurprising, then, that those with better beat perception adapted the temporal structure of their gait to be less persistent in response to an invariant stimulus. In other words, those who were better at capturing the beat within the auditory stimulus were those who were most affected by the auditory stimulation. In this case the impact was negative, with the temporal structure of gait being less persistent and less natural when walking to isochronous cues. In the context of the wider literature, the benefit to spatiotemporal parameters of gait reported in previous studies when walking to isochronous cues may come at the cost of decreased long-range correlations in gait, particularly for those with better beat perception.

Conclusion

Ultimately, the goal of this study is to contribute to our understanding of the conditions under which RAC can optimally influence gait. Our findings highlight the importance of an appropriate match between the auditory cue chosen and the target gait parameter. Fractal auditory cues are ideally suited to support the temporal structure characteristic of healthy gait. While isochronous cues have been shown to benefit various spatiotemporal gait parameters, this may occur alongside alterations to the temporal structure of gait, particularly for good beat perceivers. Those with better beat perception may show the greatest sensitivity to the match between cue type and target outcome, resulting in decreased long-range correlations under isochronous cueing. Additionally, clinicians should consider their patients' cognitive and motor profiles. Our findings suggest that healthy adults can tolerate some cognitive load and maintain gait dynamics during cued walking. However, if the attentional load becomes too high, then gait dynamics may be disrupted. Further, our results suggest that those with the least persistent long-range correlations in gait have the most to gain from walking to an auditory stimulus with a fractal patterning.

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Data availability Data will be made available on request.

Declarations

Conflict of 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.

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

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

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