The who and how of rhythmic auditory stimulation for gait rehabilitation: The impact of task demands and individual characteristics

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ABSTRACT

The who and how of rhythmic auditory stimulation for gait rehabilitation: The impact of task demands and individual characteristics

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Rhythmic Auditory Stimulation (RAS) is an intervention for gait rehabilitation in which individuals walk to an auditory cueing stimulus. While it is known that the cognitive contribution to walking increases with increasing age, the attentional demands of RAS are not well understood. Often isochronous metronome cues (i.e., with a constant inter-beat interval) are used during RAS. However, fluctuations in stride-to-stride intervals have a predictable (i.e. fractal) pattern over time, characterized by persistent long-range correlations. Walking to isochronous cues decreases long-range correlations in gait, making gait more random, while walking to a metronome with fractal-like fluctuations increases long-range correlations in gait. How cue types interact with beat perception is not known. This may be an important consideration, however, given that those with better beat perception tend to benefit more from RAS. Across the literature investigating RAS, data on middle-aged adults is lacking. We sought to better understand task parameters and individual characteristics which impact response to RAS. Paper 1 establishes the validity of footswitches to measure step-time parameters, compared against the gold standard electronic walkway. In Paper 2, young, middle-aged, and older adults walked to tones under increasing levels of task complexity. Middle-aged adults and a subgroup of older adults showed reduced step-time variability when walking to a simple beat. Among middle-aged adults, this effect was attenuated with increasing levels of task complexity. Additionally, stronger beat perception and auditory selective attention supported a positive response to cued walking. In Paper 3, young, middle-aged, and older adults walked to tones under increasing levels of attentional load. Tones were presented in isochronous and fractal rhythms. Walking to fractal cues increased long-range correlations relative to walking in silence. This increase was qualitatively greater among middle-aged adults. Walking to isochronous cues decreased long-range correlations relative to walking in silence, particularly for those with stronger beat perception. Attentional load did not modulate long-range correlations in gait. Taken together, this program of research showed dissociable effects of attentional load on the magnitude versus the pattern of variability in step-to-step fluctuations. We also highlighted important individual difference factors. These findings can help optimize RAS for gait rehabilitation.

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Contribution of Authors

The following thesis is comprised of three papers:

Paper 1 (Chapter 2)

Parker, A., & Li, K. Z. H. *Reliability and validity of step-time using a FootSwitch system* (Unpublished manuscript]. Department of Psychology, Concordia University.

Paper 2 (Chapter 3)

Parker, A., Dalla Bella, S., Penhune, V. B., Young, L., Li, K. Z. H. (2025). Walking to a beat is modulated by task complexity and individual differences in age, beat perception, and selective attention. *Journal of Adult Development.* https://doi.org/10.1007/s10804-025-09545-7

Paper 3 (Chapter 4)

Parker, A., Dalla Bella, S., Penhune, V. B., Young, L., Grenet, D., Li, K. Z. H. Tuned to walk: Cue type, beat perception, and gait dynamics during rhythmic stimulation in aging (Manuscript under review, *Experimental Brain Research*).

I was responsible for selecting and conceptualizing this program of research in consultation with Dr. Karen Z. H. Li. I met regularly with Dr. Li regarding the development and implementation of these studies, the writing of each of the studies included below, and the writing of the current document. Drs. Emily Coffey and Virginia Penhune approved of the overall methodology at my thesis proposal meeting on September 20, 2021.

For Paper 1, I was responsible for conceptualization, design, and execution of the project. This study used a sub-sample of the main sample, where I was responsible for all aspects of data collection (see below for more details on data collection). I was responsible for overseeing the data acquisition and pre-processing in consultation with David Munro and Marchiano Dong Jun Oh, respectively. I was responsible for data cleaning and conducted all of the statistical analyses. I prepared the written report and integrated feedback from Dr. Li. Dr. Li provided supervision and feedback for each of these steps.

For Paper 2, I was responsible for conceptualizing, designing, and executing the project. I consulted with Dr. Karen Z. H. Li, Dr. Simone Dalla Bella, Dr. Virginia Penhune, and Dr. Laurel Young regarding the conceptualization and study design. I was responsible for all aspects of data collection including recruiting participants, conducting assessments of motor, cognitive, and rhythmic abilities, running the experimental conditions, and training undergraduate research assistants and volunteers to conduct aspects of data collection. I was responsible for data cleaning and conducted all of the statistical analyses. I prepared the manuscript for publication and was responsible for integrate feedback from co-authors and incorporating reviewer comments. Dr. Li provided supervision and feedback on all the steps outlined above.

For Paper 3, I was responsible for conceptualizing, designing, and executing the project. I consulted with Dr. Karen Z. H. Li, Dr. Simone Dalla Bella, Dr. Virginia Penhune, and Dr. Laurel Young regarding the conceptualization and study design. The sample used was the same as for studies 1 and 2, for which I was responsible for all aspects of data collection (see above). I was responsible for data cleaning and conducted all the statistical analyses. Dr. David Grenet adapted a script for Detrended Fluctuation Analyses to be appropriate for use for our sample size; he also consulted regarding the application of linear mixed effects models. I prepared the manuscript and was responsible for integrate feedback from co-authors and submitting the manuscript for publication. Dr. Li provided supervision and feedback on all the steps outlined above.

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CHAPTER 1: General Introduction

Walking is essential for the safety and autonomy of older adults. Between 20 – 30 % of adults aged 65 and over fall each year, costing the health care system $1049 - $3611 per injurious fall (World Health Organization, 2007). Gait variability is a sensitive predictor of falls risk (Verghese et al., 2009) and is increased among older adults (Kobsar et al., 2014a). Older adults with a history of falls have increased variability in the stride-to-stride fluctuations of gait as well as a disturbance in the pattern of fluctuations over time compared to those without a history of falls (Hausdorff, 2007). Gait rehabilitation programs seek to improve the consistency and stability of gait to reduce risk of falls. Rhythmic auditory stimulation (RAS) is an intervention to rehabilitate gait and has been shown to improve gait speed, stride length, and gait variability among older adults (Ghai et al., 2018). During RAS individuals walk to an auditory pacing stimulus, usually a metronome or music. Importantly, individuals vary in their response to RAS with some showing improvements in gait and others show deleterious effects (Dalla Bella et al., 2018). Music is a complex stimulus with various elements which may impact gait differently. For example, walking to low-groove music produces a deleterious effect on gait, resulting in slower, shorter, and wider steps, particularly for those with poor beat perception (Leow et al., 2014). It is of critical importance to better understand the conditions under which RAS can produce detrimental effects on gait, and for whom.

While it is known that the cognitive contribution to walking increases in older adulthood (Yogev-Seligmann et al., 2008), relatively little is known about how varying cognitive load impacts the effect of RAS on gait. A few studies have investigated this issue using the dual-task design in which a cognitive and motor task are performed separately then simultaneously. For example, cognitive task performance has been shown to deteriorate when walking to auditory cues versus when walking in silence (i.e., there was dual-task interference), which suggests that RAS is attentionally demanding (Peper et al., 2012). However, what aspects of RAS are attentionally demanding is not well understood. Additionally, while rhythmic skills are known to influence response to RAS (Dalla Bella et al., 2017b), little is known about what other cognitive abilities may support a positive response to RAS. Further, researchers have found that the temporal structure of the cueing stimulus can negatively or positively impact the pattern of fluctuations over time, or temporal dynamics, in gait (Dotov et al., 2017). However, how/if the temporal structure of the cueing stimulus interacts with attentional load or individual rhythmic skills is less well understood. The goal of the current research program is to address these gaps in the literature by examining the impact of increasing attentional load on gait variability and temporal dynamics in gait during cued walking. We also aim to examine potential interactions with individual cognitive, motor, and beat perception ability and the temporal structure of cues.

Motor Performance and Aging

Objective Measurement of Gait

The gait cycle can be described by parameters which are characteristic of a person's walking, for example average walking speed (i.e., meters per second), average cadence (i.e., steps per minute), average stride-time (i.e., the time between one heel-strike to the next heel-strike of the same foot), or average stride length (i.e., the distance covered between one heel-strike to the next heel-strike of the same foot). Gait variability describes the magnitude of stride-to-stride fluctuations and is typically expressed as the standard deviation or coefficient of variation (i.e., CoV = *SD* / mean). Gait variability can also be described in terms of the temporal dynamics in gait, that is, the pattern of fluctuations in variability over time (Hausdorff, 2007). The pattern of fluctuations refers to *how* the stride fluctuates over time, independent of the magnitude of the fluctuation. In healthy gait, these fluctuations show a fractal-like pattern. Fractal patterns are apparent in many naturally occurring and biologically based phenomena including heart-rate variability and stride-time variability in gait (Lipsitz, 2004). These patterns are characterized by self-similarity and long-range correlations. The fluctuations are self-similar in that the fluctuations at one time scale are like the fluctuations at other time scales. For example, the fluctuations over 30 strides are like that over 300 strides, or 3000 strides, etc. Additionally, any one stride-interval is correlated with stride-intervals that occurred hundreds of strides earlier. Continuous walking data are required to capture fractal dynamics in gait with some researchers estimating 500-600 observations required (Marmelat & Meidinger, 2019), although as few as 100-200 observations can be adequate for group comparisons (Phinyomark et al., 2020). Fractal patterns can be quantified with the fractal scaling index (α) which describes the persistence of long-range correlations in gait (Hausdorff, 2007). An $\alpha < 0.5$ indicates anti-persistent correlations such that a shorter stride interval is more likely to be followed by a longer stride interval and vice versa (Goldberger et al., 2002). An $\alpha = 0.5$ indicates that stride times are uncorrelated, that is, they are random. An $0.5 < \alpha \leq 1.0$, indicates persistent long-range correlations such that a long stride interval is likely to be followed by a long stride interval, and a short stride interval by a short one. An $\alpha = 1.0$ represents the ‘ideal’ fractal index, a compromise between extreme rigidity and randomness. Values of $\alpha > 1.0$ suggest an extremely regular and rigid pattern of walking. A person with this walking pattern would have difficulty flexibly accommodating obstacles, for example. Researchers have proposed that gait which possesses fractal-like fluctuations is ideally suited to flexibly respond to a changing and unpredictable environment (Stergiou et al., 2016). From this perspective a healthy system is characterized by a balance of organization and flexibility. The breakdown of fractal dynamics in gait may manifest as pathologic periodicity (i.e. $\alpha > 1.0$), meaning excessive order which is inflexible and cannot adapt to a changing environment. Alternatively, the breakdown of fractal dynamics can result in randomness (i.e. α towards 0.5), where walking behavior is disorganized.

Changes to Gait in Aging

Walking speed, cadence, and stride length decrease with increased age (Hausdorff, 2007). Preferred gait speed over a short distance is an important indicator of overall health, and significantly predicts disability, cognitive impairment, falls, and survival among healthy older adults (Abellan Van Kan et al., 2009). Healthy older adults with a walking speed of < 1.0 meters/second are at increased risk for adverse health outcomes (Abellan Van Kan et al., 2009). Gait variability increases with increased age (Kobsar et al., 2014a) and higher stride-time variability predicts future falls in older adults (Hausdorff et al., 2001). Gait variability may be a more sensitive predictor of falls risk compared to other spatiotemporal parameters of gait. Older adults with a history of falls have higher stride-time variability compared to older adults with no history of falling, even when there are no differences in gait speed between groups (Hausdorff et al., 1997). Stride length variability and swing time variability are known to predict injurious falls, whereas gait speed and mean stride length do not (Verghese et al., 2009). Gait variability is also sensitive to dual-task manipulations (Al-Yahya et al., 2011), and gait variability under dual-task conditions predicts future falls (Herman et al., 2010). The research described above positions gait variability as a clinically meaningful measure of gait. Stride time variability is the most widely reported measure of gait variability (Montero-Odasso et al., 2012).

The temporal dynamics in gait also shift with aging. The fractal scaling exponent (α) of gait, which describes the persistence of long-range correlations, in young adults is approximately 0.85 compared to 0.75 in healthy older adults (Kobsar et al., 2014a). Age-related differences the temporal dynamics in gait are observed even when other measures, such as stride-time variability, are similar between young adults and older adults (Hausdorff, 2007). Less persistent long-range correlations in gait have been shown to discriminate between older adults with and without a history of falls (Herman et al., 2005). More research is needed to fully describe the functional implications of less persistent long-range correlations in gait with aging. How temporal dynamics in gait may change in mid-life is relatively unknown. In one study, middle-aged healthy controls had a fractal scaling exponent (α) of 0.73 in gait (Homs et al., 2022). In another study, middle-aged adults had a fractal scaling exponent (α) of ~ .90 for all physical activity (i.e., bathing, swimming, walking, etc) with higher scaling exponents associated with better performance on verbal fluency task for males but not females (Blodgett et al., 2023). More research is needed to characterize the temporal dynamics of gait among middle-aged adults.

Cognitive and Automatic Control of Gait

Gait as a Semi-Automatic Motor Task

To understand how gait is achieved, it is useful to situate ourselves within the motor hierarchy (Mason, 2017). The lowest element in the motor hierarchy are motoneurons and motor interneurons located in the spinal cord. Sensory afferents from muscle and skin send information to motoneurons and motor interneurons which elicit reflexive adjustments, for example, a twitch. The next level of the motor hierarchy is made up of central pattern generators located within the spinal cord and brain stem. Central pattern generators are circuits of neurons that produce patterned motor output such as walking and chewing. At the highest level of the motor hierarchy are cortical motor control circuits, which are responsible for purposeful and voluntary movement. Motor programs for purposeful action (e.g., walking to the store) and anticipatory postural control originate in the motor control centers in the forebrain (e.g., the supplementary motor area, premotor area, and primary motor cortex), with modulatory input from the cerebellum and basal ganglia, and travel down the motor hierarchy in an integrated fashion (Takakusaki, 2017).

Walking is more complex than a reflex but does not require deliberate conscious control for every step and is therefore termed semi-automatic (Mason, 2017). Central pattern generators in the spinal cord generate the basic rhythmic and patterned movements of stepping and central pattern generators in the midbrain initiate gait and coordinate the two legs with the arms, shoulders, and head. While central pattern generators do not require sensory input nor reflexes, without these walking would be stereotyped and only function under ideal circumstances. Reflexes are necessary to adjust for different loads, for example, to navigate unexpected changes in surfaces. Investigators have also found that gait depends on higher-order cognitive processes beyond motor control centres in the cerebral cortex, and increasingly so with aging (Seidler et al., 2010).

Loss of Automaticity in Gait with Aging

Automatic control of walking is defined as walking with minimal recruitment of attentional and executive functioning resources (Montero-Odasso et al., 2012). With increased age, greater cognitive resources are required to execute walking and to maintain balance as evidenced by correlational, experimental, and neuroimaging research. Among older adults, less variable and more stable gait is associated with better performance on tests of executive functioning (Hausdorff et al., 2005). Further, healthy older adults with poorer executive functioning are at higher risk for future falls, while memory does not predict future falls (Herman et al., 2010). Dual-task walking (i.e., walking while concurrently performing a secondary cognitive task) draws on attentional and executive function resources (Yogev-Seligmann et al., 2008). Numerous experimental studies have demonstrated that gait variability increases under dual-task relative to single-task conditions among older adults (Smith et al., 2017). Further, gait variability of older adults under dual-task conditions is associated with future falls (Mirelman et al., 2012). Finally, smaller grey matter volumes in prefrontal cortex are associated with slower gait speed among healthy older adults (Rosano et al., 2007), and prefrontal activity is higher among older adults compared to young adults when walking (Hoang et al., 2022).

These findings highlight the role of attentional and executive function resources in maintaining consistent gait and safely ambulating in older adulthood. This is a critical issue. In healthy gait, automatic and executive control processes are complementary (Clark, 2015). Automatic control processes can, for example, quickly adjust for the changes in the walking surface to ensure safe walking. Executive control processes can be applied in novel situations, but are slow, effortful, and can be overwhelmed by complex environmental conditions. When everyday walking requires increased executive control, as in aging, fewer cognitive resources can be devoted to other tasks, for example, monitoring for hazards in the environment. Increased attentional and executive control in walking in older adulthood therefore has implications for the safe ambulation and health of older adults.

Cognitive and Brain Aging

Alongside age-related changes to gait, the cognitive abilities (e.g., attentional and executive control) that motor performance increasingly relies on with increased age are themselves undergoing age-related changes. Executive functions are domain-general higher-order cognitive processes, such as updating, inhibition, and switching (Miyake et al., 2000). Working memory/updating capacity decreases linearly across the adult lifespan (Park et al., 2002), which may be a product of age-related decline in inhibition, or the ability to suppress or delete irrelevant data (Lustig et al., 2007). Older adults show larger global switching costs relative to younger adults (Braver & West, 2011). Divided attention is a special case of attention which is considered an executive function (Li et al., 2017). Divided attention is required during the simultaneous performance of two tasks (i.e., dual-tasking) and older adults consistently show larger costs to performance when dual-tasking compared to young adults (Verhaeghen, 2011). These age-related performance declines occur in the context of selective atrophy (i.e., decreases in grey matter volume) to the frontal and temporal regions of the brain in healthy aging (Raz et al., 2007). Volumetric declines are particularly pronounced in the prefrontal cortex (Raz et al., 1997).

The pattern of brain activity during cognitive task performance also differs between young and older adults. Specifically, older adults recruit additional prefrontal brain regions relative to young adults during cognitive task performance (Nielson et al., 2002). Increased brain activation is thought to be compensatory when is it associated with the maintenance of cognitive task performance in older adulthood (Reuter-Lorenz & Park, 2024). Similar patterns of brain activity have been observed during motor task performance. For example, activation in the prefrontal cortex during single-task walking is increased in older adults as compared to young adults (Hoang et al., 2022). These studies show that older adults recruit greater prefrontal resources during cognitive and motor task performance as compared to young adults.

Further, cognitive and motor aging interact with auditory aging. In healthy adults greater hearing impairment is associated with poorer mental status, memory, and executive functioning (Lin et al., 2011). Longitudinally, poorer baseline hearing predicts poorer verbal short-term memory performance 2 years later (Armstrong et al., 2018). Additionally, hearing impairment has been associated with increased risk for falls (Kamil et al., 2016; Wang et al., 2022).

Taken together, increased cognitive control of walking consistency and balance occurs in the context of normative age-related decline in cognitive and auditory systems. Older adults show greater recruitment of neural resources during cognitive and motor performance as a single task, leaving fewer resources available to perform other tasks concurrently such as monitoring the environment for hazards. In this way, experimental dual-task designs can provide useful information about the capacity of older adults to navigate environmental demands during walking. Dual-task paradigms which involve auditorily presented inputs should also consider age-related hearing loss.

Cognitive-Motor Dual-Tasking

Changes to performance under dual-task relative to single-task conditions are characterized by a dual-task cost (DTC) score where DTC% = (single-task performance – dual-task performance) / single-task performance × 100%. The formula can be reversed for variables in which a higher value indicates poorer performance. Accordingly, a positive DTC score indicates a higher cost to performance under dual-task relative to single-task conditions. Conversely, a negative DTC score indicates an improvement in dual-task performance relative to single-task performance, also called a facilitation effect. It is important to quantify costs in both the cognitive and motor domains as cost and facilitation effects can be observed in one domain, in both domains, or in neither domain, with different implications for each case (Plummer & Eskes, 2015).

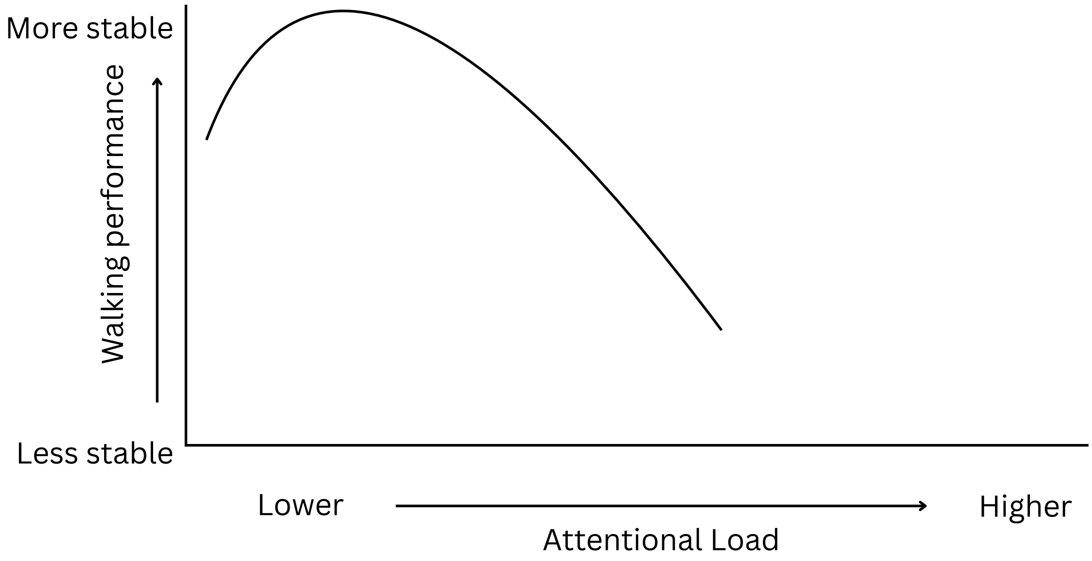
When dual-task costs are observed in both domains this suggests that attentional demands exceed total resource capacity (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2008). Capacity-sharing models suppose that cognitive capacity is a limited resource and that the simultaneous performance of two tasks will result in dual-task costs if the two tasks draw on the same cognitive resources, and if task demands exceed the individual’s total capacity (Tombu & Jolicoæur, 2003). For example, in one study middle-aged and older adults, but not younger adults, showed DTC in variability of velocity in walking (Hollman et al., 2007). Errors on the concurrently performed cognitive task and walking variability were positively correlated only among older adults, such that older adults who struggled more with the cognitive task also showed more variable walking under dual-task conditions. This is consistent with a capacity sharing model and suggests that capacity for dual tasking is lower among older relative to middle-aged and younger adults.

Postural prioritization is a concept to explain the presence of dual-task costs in the cognitive domain while performance in the motor domain is maintained relative to single-task conditions. Postural prioritization, or using a “posture first” strategy, supposes that healthy individuals will minimize danger (i.e., falling) by prioritizing maintaining balance while walking over performance on a secondary cognitive task (Yogev-Seligmann et al., 2012a). Consistent with this, older adults tend to prioritize performance in the walking task during cognitive-motor dual-tasking (Li et al., 2001; Nieborowska et al., 2019), particularly when the difficulty of the secondary cognitive task is high (Goh et al., 2021). However, individuals may also adopt a “posture second” strategy. For example, older adults with Parkinson’s Disease and healthy controls have shown DTC in walking speed while maintaining performance on a verbal fluency relative to single-task conditions (Yogev-Seligmann et al., 2012b). A “posture-second” strategy has been observed among older adults with poor cognitive flexibility and may reflect poor resource allocation (Hobert et al., 2011). Alternatively, older adults with sufficient postural “reserve” (i.e., the ability to respond to a postural threat) may be able to prioritize cognitive task performance and safely accrue costs in walking performance without significantly increasing their risk of falling (Holtzer et al., 2014).

The resource capacity and prioritization views are helpful to interpret costs during cognitive-motor dual-tasking. However, neither view alone can account for both facilitative and interference effects while dual tasking. The dual-process model is an integrative model which accounts for both facilitation and interference effects in the motor domain (Huxhold et al., 2006). Research has shown that inducing an internal focus of attention interferes with automatic control processes (Wulf et al., 2001), resulting in poorer postural control when attention is directed towards motor performance as compared to when attention is directed externally (Kal et al., 2013; McNevin et al., 2003; Vidal et al., 2018). In the first process of the dual-process model, adding a secondary cognitive task of low cognitive load improves motor performance by shifting attention externally and away from motor performance, thereby enabling automatic control processes. In the second process, a secondary task with a high cognitive load interferes with motor performance via cross-domain resource competition. The dual-process model proposes that there is a U-shaped relation between motor performance and cognitive load such that there is an optimal cognitive load to benefit motor performance with costs to motor performance occurring when the load is too low or too high (see *Figure 1* for a conceptual diagram by the

Figure 1

Visual Representation of the Dual-Process Model



author for the purpose of this dissertation). Importantly, what constitutes a “high” versus “low” cognitive load, and thus the turning point at which improvement by the first process is overridden by interference by the second process, depends on individual cognitive capacity.

Empirical studies of the dual-process model report different patterns of facilitation and interreference among young versus older adults. In one study older adults showed improved postural stability with the introduction of a low cognitive load, with costs to postural sway with increasing cognitive load (Huxhold et al., 2006). Young adults’ postural performance, however, was not affected by increasing cognitive demands of the secondary task. Lövdén and colleagues (2008) extended these findings to gait variability. In their study, older adults showed an improvement in stride-time variability relative to single-task walking when concurrently performing a 1-back task. With increasing task difficulty (i.e., 2-, 3-, and 4-back), the stride-time variability of older adults increased. Young adults, however, continued to show reduced stride-time variability at increased levels of difficulty of the cognitive task. In another study, a U-shaped relation between step-time variability and difficulty of a dichotic listening task was observed for older adults, whereas young adults showed facilitated gait rhythmicity in all conditions (Decker et al., 2016). These studies demonstrate that the inflection point of the U-shaped curve predicted by the dual-process model occurs at different levels of task complexity for young and older adults. Differences in the pattern of complexity effects between young and older adults were attributed to age-related differences in cognitive capacity. These studies also demonstrate the usefulness of a research design involving incremental increases in cognitive load to detect age-related differences in interreference and facilitation effects during cognitive-motor dual-tasking.

Rhythmic Auditory Stimulation: Adding a Secondary Task to Improve Gait

Walking to a rhythmic beat, termed Rhythmic Auditory Stimulation (RAS), is an intervention for gait rehabilitation and is effective for improving gait velocity, stride length, and stride-time variability among young and older adults (Ghai et al., 2018). Researchers have made efforts to define the conditions under which RAS can optimally influence gait, and I will argue that viewing RAS through a dual-task lens can further this effort.

Research has shown that individuals instructed to match their steps to a metronome adapt their gait speed to match the tempo (i.e., beats per minute) of the metronome beat, whether it be faster or slower than their preferred walking speed (Hoppe et al., 2020). Thus, if the goal is to improve walking speed, then the auditory stimulus should be set to be faster than preferred walking speed (e.g., Nascimento et al., 2020). Walking to a metronome at both 100% and 110% of preferred walking speed results in longer strides among older adults (Minino et al., 2021). Tempos of 22.5% faster than preferred cadence may be too challenging for some older adults (Roerdink et al., 2011). Whether music or metronome is more effective for RAS may depend on age. In one study, healthy young adults walked faster to music and healthy older adults walked faster to a metronome (Roberts et al., 2021). However, music is a complex stimulus with diverse elements which may differentially impact gait.

Musical groove is defined as wanting to move some part of the body to music (Madison, 2006). High-groove music has been shown to elicit faster and longer steps than low-groove music (Leow et al., 2015). Researchers tested the hypothesis that the beneficial effect of high-groove music on walking performance is due to higher beat salience relative to low-groove music, that is, the music having a stronger beat (Leow et al., 2021). The researchers asked participants to walk to high- and low-groove music with and without an embedded metronome. Similar to previous studies, gait was faster and less variable when walking to high-groove relative to low-groove music. Embedding low-groove music with a metronome beat improved gait speed relative to low-groove music without a metronome. Gait variability, however, was similar when walking to low-groove music and to low-groove music embedded with a metronome. The researchers concluded that high-groove music elicits better walking performance than low-groove music in part, but not in whole, due to increased beat salience.

Many studies investigating RAS use an isochronous auditory beat as a pacing stimulus, that is, a stimulus in which all inter-beat intervals are of equal duration. Walking to isochronous auditory cues benefits average spatiotemporal parameters of gait, for example resulting in increased stride length in older adults (Minino et al., 2021). However, as discussed above, inter-step intervals of healthy gait are not perfectly spaced but rather exhibit natural variability characterized by long-range correlations. Walking to isochronous auditory cues decreases the persistence of long-range correlations in gait among people with Parkinson's Disease (Dotov et al., 2017; Lheureux et al., 2020). In contrast, people with Parkinson's Disease and healthy older adult controls show increased (i.e., improved) α-values when walking to metronome cues with fractal patterning (i.e., which mimic the naturalistic variability of healthy gait; Marmelat et al., 2020). Middle-aged adults are less well represented in the literature. In one study, middle-aged adults showed improved stride-time variability and stride-length variability during treadmill walking with isochronous metronome cues (Terrier & Dériaz, 2012). Temporal dynamics of stride time, stride length, and stride speed, however, exhibited anti-persistence when walking to isochronous metronome cues. How the temporal structure of the auditory cueing stimulus impacts the gait of individuals with different cognitive, motor, or rhythmic profiles is not well-understood.

Task instruction may also impact the response to RAS. In healthy young adults, explicit instructions to synchronize footsteps to the beat during cued walking has resulted in slower, shorter strides compared to when no instruction is given (Leow et al., 2018). Explicit instructions to synchronize footsteps to the beat has also resulted in improvements in gait speed among young (Leow et al., 2015) and older adults (Ready et al., 2022). Among people with Parkinson's Disease, instructions to synchronize to the beat has resulted in lower step-time variability (i.e., more consistent walking) relative to uncued walking (Baker et al., 2008). Further, young adults who are poor beat perceivers showed better balance (i.e., more narrow strides) when walking freely to cues whereas good beat perceivers showed better balance when instructed to synchronize (Ready et al., 2019). The effect of instructions to synchronize to the beat are not straightforward and may depend on population examined and beat perception ability.

Beat perception and rhythmic skills may be a particularly important construct in predicting response to RAS. People with Parkinson's Disease who show a positive response to RAS tend to be more musically trained, have better self-reported music perception, synchronize their walking to cues to a greater extent, and have poorer executive functioning compared to patients showing a neutral or negative response to cued walking (Cochen De Cock et al., 2018). A positive response to musically-cued gait training has also been predicted by synchronization ability in both tapping tasks and synchronizing steps to cues, as well as more severe gait impairment (Dalla Bella et al., 2017b). Beat perception ability also interacts with musical groove during cued walking such that the deleterious effects of low-groove music on gait (reviewed above) are particularly pronounced among young (Leow et al., 2014) and older adults (Leow et al., 2021) with poor beat perception. The authors speculated that synchronizing to auditory cues is cognitively demanding, particularly for those with poor beat perception.

Supporting the view that walking to rhythmic cues is attentionally demanding, researchers have found increased cortical activity in prefrontal regions during cued walking as compared to walking in silence (Vitorio et al., 2018). Only a small number of studies have added an unrelated cognitive task during cued walking to investigate the attentional demands of RAS. As I will outline below, the current research program conceptualized RAS itself as a dual-task situation in which walking is the primary task and synchronizing steps to tones is the secondary task. From this perspective, adding an unrelated cognitive task during cued walking effectively results in a "triple-task" situation. The studies discussed below refer this situation as a dual-task or as performing a dual-task during auditory cueing. The nomenclature of a "secondary" cognitive task is retained in the discussion below to align with the intent of the authors conducting the research.

In one study, reaction times of young and older adults during a probe reaction time task were longer when walking with metronome cues as compared to when walking in silence, suggesting that walking to auditory cues is attentionally demanding (Peper et al., 2012). In another study, young adults walked under instructions to attend to music, to attend to a semantic monitoring task with music present, and to attend to both the music and the task (Leow et al., 2018). Young adults walked with slower and shorter strides when attending concurrently to music and the secondary cognitive task compared to when attending to music without the task. This suggests that diverting attentional resources away from music during cued walking hinders gait. In another study older adults walked in silence, while synchronizing their steps to metronome cues, while performing a serial-3 subtraction task, and while synchronizing to metronome cues and performing a serial-3 subtraction task (Hamacher et al., 2016). Gait variability was *increased* during cued walking relative to walking in silence. Performing a secondary cognitive task during cued walking *decreased* gait variability relative to cued walking without the task. The authors attributed the increase in gait variability during cued walking relative to walking in silence to the imposition of an internal focus of attention which disrupted automatic control in gait (Wulf, 2013). They posited that adding a cognitive load released the internal focus, thereby returning walking performance closer to baseline levels.

While the studies reviewed above all point to a role of attention during cued walking, the effects on gait differed. Auditory cues may facilitate an attentional bias towards walking performance which in some instances improves gait performance (e.g., Vitorio et al., 2018) and in some instances hinders gait performance (e.g., Hamacher et al., 2016) relative to walking in silence. Adding an unrelated cognitive task to cued walking may result in poorer (Leow et al.,

2018) or improved (Hamacher et al., 2016) gait performance relative to auditory stimulation alone. Peterson and Smulders (2015) have proposed that drawing attention towards gait may facilitate motor performance during difficult circumstances or in impaired populations, and that synchronizing steps to auditory cues may compete for limited attentional resources and impair gait during complex tasks. To my knowledge, no study has systematically manipulated the complexity of the secondary task during cued walking. This research strategy may be useful to disentangle the mixed results reported in the literature regarding the effects of attentional load on gait during cued walking. As reviewed above, complexity effects during dual-tasking can be interpreted through a dual-process lens to better understand beneficial and deleterious effects of RAS on gait (Huxhold et al., 2006).

Rationale and Current Program of Research

In summary, RAS is an effective intervention to improve gait in older adults (Ghai et al., 2018). A tempo of the auditory cueing stimulus of approximately 110% of preferred walking speed is effective in improving gait speed among older adults (Nascimento et al., 2020). Isochronous cues have been shown to benefit gait speed and stride length (Minino et al., 2021), while fractal cues may be better suited to support long-range correlations in gait dynamics (Marmelat et al., 2020). Additionally, response to RAS is impacted by individual differences in motor (Dalla Bella et al., 2017b), cognitive, and beat perception abilities (Cochen De Cock et al., 2018). Beat perception can also interact with task parameters to produce different effects on gait (Leow et al., 2021). Across the literature reviewed above, data on middle-aged adults is lacking. Whether midlife is simply "in between" young and late adulthood or represents a qualitatively different life stage is an empirical question for which we have little data. Studies of dual tasking during RAS suggest that RAS is attentionally demanding (Peper et al., 2012), although task conditions which may lead to negative or positive effects on gait are not well-understood.

In the current program of research, we conceptualize RAS within a cognitive-motor dual-tasking framework. From this perspective the purpose of adding a secondary task (i.e., synchronizing steps with a beat) is to produce a facilitative effect (i.e., to improve walking performance) relative to walking in silence. We propose that the dual-task design is a useful research strategy for investigating cognitive-motor interactions during RAS. Further, the dual-process model (Huxhold et al., 2006), while underexplored, may be useful in interpreting beneficial and deleterious effects on gait within this context. With this framework in mind, the current studies aim to better define the conditions under which attentional load is likely to benefit versus interfere with gait in aging within the context of RAS. In Paper 1 we investigated the reliability and validity of footswitches to capture gait against the gold standard of an electronic walkway. In Paper 2 we manipulated cognitive load during RAS with isochronous cues among young, middle-aged, and older adults and observed the impact on gait variability with the aim of interpreting interference and facilitation effects. In Paper 3, we manipulated the temporal structure of cues (i.e., isochronous versus fractal) and observed the effect on the temporal dynamics of gait and explored any interactions with attentional load and beat perception. Overall, we expected that the benefit of RAS on gait would be attenuated in conditions of increasing cognitive load, particularly for older adults. We also expected that fractal cues would be more beneficial than isochronous cues in terms of improving the long-range correlations in gait. Finally, we expected that poor beat perceivers would be disadvantaged relative to good beat perceivers during RAS.

CHAPTER 2: Reliability and validity of step-time using a FootSwitch system during cued and uncued walking

Accurate measurement of gait is critical to research investigating mobility, falls risk, and health in aging. The most commonly used instrument to measure gait is an overground electronic walkway (Lord et al., 2011). Overground electronic walkways are valid and reliable tools for the measurement of gait; however, they have a limited ability to capture continuous walking. Footswitches attach to the heel and toe of the shoe or foot and can capture continuous walking data. Clinical footswitch systems have been shown to be reliable and valid tools to measure gait. The reliability and validity of laboratory footswitch systems to capture gait, particularly across different age groups, is less well-understood.

Electronic walkways are pressure-sensitive mats, varying in length, and have been shown to be valid tools for measuring spatial-temporal gait parameters (McDonough et al., 2001). Mean values have fair to excellent test-retest reliability (Almarwani et al., 2016; Hars et al., 2013; Van Uden & Besser, 2004) while measures of gait variability show poor to good test-retest reliability (Brach et al., 2008; Hars et al., 2013; Hollman et al., 2010). The relatively lower reliability of gait variability in the literature as compared to mean parameters may be due to the number of gait cycles required to produce an accurate estimate. While only 10 gait cycles are needed to show excellent reliability for mean gait parameters, 50 gait cycles were needed to achieve reliable results for gait variability (König et al., 2014). Given its demonstrated reliability and ease of use, it is not surprising that electronic walkways are a common tool to capture gait (Lord et al., 2011). They have also been used as the gold standard against which other instruments, such as accelerometers, observational ratings, and floor-based photocell systems, have been tested (Hartmann et al., 2009; Huang et al., 2008; Lienhard et al., 2013). Electronic walkways have some limitations, however. For example, they are designed for use in limited settings (e.g., they are not designed to accommodate turns). They are generally 3.5 to 9 meters long can therefore only collect a relatively small number of consecutive steps. For example, approximately 10 strides per pass are collected on a 6.4-meter-long walkway (Commandeur et al., 2024). Continuous walking data may be more reliable as compared to interrupted walks (Lord et al., 2011).

Footswitches are wearable, pressure sensitive sensors that can be attached to heel and toe. They are portable and can therefore be used in a variety of settings and can collect continuous gait data over a long period. The ability to continuously collect gait data is a significant strength if one is aiming to measure gait variability (König et al., 2014). Indeed, the measurement of fractal patterns in stride-to-stride fluctuations requires 500-600 continuous footsteps to produce accurate estimates (Damouras et al., 2010; Marmelat & Meidinger, 2019; Phinyomark et al., 2020). Gait variability is a sensitive predictor of falls risk and is therefore an important clinical parameter (Hausdorff, 2007). Given that footswitches are ideally suited to collect continuous time series data of longer durations, they may be practical in a clinical and laboratory setting.

The Clinical Stride Analyzer, a clinical footswitch system, has demonstrated excellent test-retest reliability among stroke patients (Hill et al., 1994) and among patients with Parkinson's Disease and healthy controls (Morris et al., 1996). The Clinical Stride Analyzer has also shown good sensitivity (80%) and specificity (89%) as a screening tool for balance and mobility impairments in older adults (Harada et al., 1995). Laboratory footswitch systems for the measurement of gait also show high test-retest reliability (Mills et al., 2007).

Footswitch systems and electronic walkways have shown excellent concurrent validity. For example, the GAITrite electronic walkway showed excellent concurrent validity with the Clinical Stride Analyzer footswitch system for gait speed, stride length, and cadence (Bilney et al., 2003). In another study, SMTEC footswitches showed excellent concurrent validity with the GAITrite electronic walkway for step time, stride time, and swing time at preferred and slow walking speeds, though validity for fast walking speeds was lower (Beauchet et al., 2008).

To our knowledge no studies report on the reliability or validity of footswitch systems during cued walking, though this would be important to document given the relevance of cued walking for gait rehabilitation in aging (Ghai et al., 2018). Further, while footswitches have shown to be a valid tool to measure gait variability among older adults (Kobsar et al., 2014b), direct age-related comparisons are lacking.

The purpose of this study was to estimate the immediate reliability and concurrent validity of the mean and standard deviation of step-time as measured by Noraxon DTS FootSwitches against a criterion system, the ProtoKinetics Zeno Walkway. Participants were young, middle-aged, and older adults, and completed overground walking trials of approximately 2 minutes long. Participants walked in silence (*Uncued* condition) or walked to a metronome beat (*Cued* condition). We predicted that the footswitches would show excellent reliability and validity and that this would not differ as a function of condition or age group.

Method

Participants

Young adults (aged 18-35 years) were recruited through Concordia University's participant pool. Middle-aged (aged 50-60 years) and older adults (aged 61-85 years) were recruited through flyers distributed on social media and on campus, and existing contact lists. Middle-aged and older adults received an honorarium for their participation, and young adults received course credit. This project received approval from the University Human Research Ethics Committee of Concordia University. Walking data were collected for 27 young adults, 20 middle-aged adults, and 21 older adults. Data for 17 young adults and 6 older adults were collected before an audio signal marking the start and end of the trial was integrated into the design and therefore were not eligible for the current analyses. In 33 trials (18%; impacting partial data for 7 young adults, 5 middle-aged adults, and 4 older adults) a noise signal produced by PKMAS obscured the audio signal which marked the start of the task. The data for 8 participants (3 older adults, 5 middle-aged adults) were corrupted and could not be recovered. Given that data were incomplete due the technical failures, they were considered missing completely at random. In total, data were retained for 22 participants in the *Uncued* condition (3 young adults, 11 middle-aged adults, and 8 older adults), and 27 participants in the *Cued* condition (6 young adults, 12 middle-aged adults, and 9 older adults). Participants were fluent in English, able to walk without assistive devices, and were healthy (i.e., absence of neurological, cardiovascular, orthopedic, and musculoskeletal conditions that affect their mobility or cognition, absence of diagnosed hearing impairment or uncorrected visual impairment). Participants were excluded if they scored < 26/30 on the Montreal Cognitive Assessment (MOCA; Nasreddine et al., 2005) in conjunction with scores on 2 or more neuropsychological tests which were below two standard deviations below the mean of age-matched normative data. Participants were also excluded if they obtained a pure-tone average (PTA) threshold > 25 dB HL, suggesting hearing impairment. Pure-tone audiometry (Maico 42) was used to determine the participant's PTA, defined as the quietest threshold at which they can detect pure tones averaged across 500, 1000, 2000, and 4000 Hz in the better ear. Thresholds were tested at a range from 250 Hz to 8000 Hz in both ears following the modified Hughson-Westlake procedure as recommended by the American Speech-Language-Hearing Association (Schlauch & Nelson, 2015). Briefly, the researcher decreased the sound intensity by 5 dB after the participant responded to a pure-tone signal and increased the intensity by 10 dB when the participant did not respond, to determine the lowest sound intensity that a participant could detect.

Procedure

Participants walked around an elliptical track (2.2 x 9.07 meters) in silence at their preferred walking speed (*Uncued* condition) and while synchronizing their footsteps to a series of tones (*Cued* condition). The tones were generated in MATLAB version 9.4 R2018a (MathWorks, 2018) and were presented using Avantree wireless over-the-ear headphones. The pitch of the tones was 750Hz, and tones were presented in an isochronous rhythm at a rate of 10% faster than the participant's walking speed, measured at the beginning of the session, at a volume 50 dB higher than their PTA. Participants walked around the track in a clockwise and a counterclockwise direction resulting in two trials per condition. Trial length was approximately 2 minutes.

Gait was captured with two measurement devices. A ProtoKinetics Zeno Walkway, a pressure sensitive overground mat (Zenometrics LLC, 2015), ran the length of one side of the elliptical track. Participants also wore Noraxon DTS FootSwitches (Noraxon, 2013), which are pressure sensitive sensors which attached to the heel and toe of their shoes, which collected data throughout the entirety of the trials.

Data Acquisition

The experimental setup is depicted in *Figure 1*. The Noraxon wireless telemetry system recorded the signals, sampled at a rate of 1500Hz, from the footswitches the participants were wearing. The ProtoKinetics Zeno Walkway measured gait data using pressure sensors with a sampling rate of 120Hz embedded in the mat the participants walked over. The acquired data was stored by the Noraxon Telemyo software (Noraxon, 2013) and ProtoKinetics Movement Analysis Software (Zenometrics LLC, 2015). The wireless audio aspect of the experimental setup was implemented using a Bluetooth transmitter (Priva III), headphones (Audition Pro) and receiver (Roxa Plus) all made by the same manufacturer (Avantree). The audio tones generated in MATLAB (MathWorks, 2018) were sent via the Priva III transmitter to the Bluetooth headphones worn by the participant and to the Bluetooth receiver. The Bluetooth devices were paired using the same low latency codec (aptX-LL) ensuring the signals were synchronized to within a few milliseconds. The audio signal from the Bluetooth receiver was connected to a custom audio detection circuit that generated a 200 millisecond 5-volt TTL (transistor-transistorlogic) pulse synchronized with each audio tone the participant heard. The TTL pulses were inverted (to facilitate signal processing) and sent to both the Noraxon DTS receiver (via the wireless DTS Analog Input Probe) and to the Zeno Walkway interface. These sync pulses were recorded by the Telemyo and PKMAS software to allow for comparison of the footswitch and walkway data with the audio tones presented to the participants, and to be able to anchor the two sets of data in a common time frame. Hardwired connections were made using standard 3.5mm audio jacks and cabling.

Data Pre-Processing

The data obtained from the ProtoKinetics Zeno Walkway was cleaned using PKMAS. The first and last steps of each pass were removed to decrease the impact of turns on gait parameters. Mean (*M*) and standard deviation (*SD*) of step-times acquired from the Zeno Walkway were calculated using PKMAS. To calculate equivalent *M*/*SD* from the footswitch system, we first needed to isolate the steps obtained from the Noraxon DTS FootSwitches that occurred when the participant was on the ProtoKinetics Zeno Walkway. This was possible as the auditory signal was synchronized between the Zeno Walkway and the Noraxon DTS FootSwitch datasets (see data acquisition procedure, above) and was used to mark a common Time 0 between the two datasets. Once a common Time 0 was established, the windows of time in which the participant was on the gait mat were determined. Footsteps in the Noraxon DTS FootSwitch data that occurred within these time windows were retained, while steps occurring outside these windows were removed. Pre-processing of the Noraxon DTS FootSwitch data and calculation of *M* and *SD*s for retained steps were done using a custom-developed Python script.

Statistical Analyses

Immediate reliability was assessed by computing intra-class correlations (ICCs) for the *M* and *SD* of step-time between the two trials, for each measurement device, and each condition, separately. Each trial contained a median of 6 passes on the Zeno Walkway and 42 steps. ICCs were interpreted as follows: < 0.4, poor; 0.4 - 0.59, fair; 0.60 - 0.75 good; > 0.75, excellent (Cicchetti, 1994). Criterion validity was assessed in two ways. First, ICCs were applied to the *M* and *SD* of step-time across the two measurement devices, averaged across the two trials. Second, Bland-Altman plots using the Limits of Agreement (LoA) were constructed (Altman & Bland, 1983). QQ-plots indicated that the differences of the *M*s and *SD*s were not severely non-normal, see *Figure 2*. Bias (i.e., the mean of differences) and range of agreement were calculated and superimposed on Bland-Altman plots. Finally, ICCs assessing reliability and validity of the FootSwitch system were calculated separately for each age group to examine any differences as a function of age. For all ICCs, a two-way mixed effects model, with absolute agreement, based on a single rating, was chosen based on previous recommendations (Koo & Li, 2016).

Results

Reliability

The reliability of each measurement device was assessed separately by calculating the intra-class correlation (ICC) across 2 trials, within each device, see *Table 1*. Overall, the ProtoKinetics system showed excellent reliability (ICCs > 0.84, *p*s < 0.05) except for the step-time *SD* in the *Cued* condition, which showed good reliability (ICC = 0.62, *p* < .001). The *M* step-time values derived from the Noraxon DTS FootSwitches showed excellent reliability (ICCs > 0.96, *p*s < 0.05), while the step-time *SD* values showed fair (ICC = 0.39, *p* =0.021) and good (ICC = 0.59, *p* = .002) reliability in the *Cued* and *Uncued* conditions, respectively.

Concurrent Validity

To assess the agreement between scores obtained from the Noraxon DTS FootSwitches with scores obtained from the criterion ProtoKinetics Zeno Walkway, ICCs were applied to the data, see *Table 2*. Overall, step-time *M*s showed excellent validity (ICCs > 0.99, *p*s < 0.05), while the step-time *SD*s showed poor validity for the *Uncued* condition (ICC = 0.23, *p* = .14) and fair validity for the *Cued* condition (ICC = 0.40, *p* = .02). Both step-time *M* and *SD* had low mean bias suggesting measurement devices were within 1-2 milliseconds of each other, see *Table 2*. The Limits of Agreement (LoA) were narrower, indicating higher agreement, for step-time *M* values as compared to step-time *SD* values, see *Figure 3*. A negative trend was evident in the Bland-Altman plots for step-time *SD* in the *Cued* and *Uncued* conditions. Follow-up correlational analyses showed that this trend was statistically significant for the *Cued* (*r* = -0.666 *p* < .001) but not the *Uncued* (*r* = -0.275, *p* = 0.215) condition.

Age-Related Comparisons

Reliability was calculated for each age group separately and is presented in *Table 3*. The values for both the *M* and *SD* among middle-aged and older adults were good to excellent (ICCs = 0.72 – 0.99, *p*s < 0.05) except for step-time *SD* in the *Uncued* condition among middle-aged adults which was fair (ICC = 0.49, *p* = 0.06). For young adults the *M* of step-time showed excellent reliability (ICCs = 0.88 – 0.95, *p*s < .05) while the *SD* of step-time for young adults showed the lowest ICCs, which were also not statistically significant (ICCs = 0.06 – 0.86, *p*s > 0.05).

Mean step-time showed excellent validity across conditions and age groups (ICCs => 0.99, *p*s < 0.05), see *Table 4*. Validity for the *SD* of step-time was particularly low for middle-aged adults (ICCs = 0.05 – 0.06, *p*s > 0.05) and was fair among younger and older adults (ICCs = 0.41 – 0.45, *p*s > 0.05) though not statistically significant. The only exception was the step-time *SD* in the *Cued* condition among older adults, which showed excellent reliability (ICC = 0.77, *p* = 0.003).

Discussion

The purpose of this study was to assess reliability and concurrent validity of step-time as measured by Noraxon DTS FootSwitches against the gold standard ProtoKinetics Zeno Walkway. We found that both the Noraxon footswitch and ProtoKinetics electronic walkway systems showed excellent test-retest reliability for step-time mean. The reliability of standard deviation of step-time was lower for both systems in comparison. Further, the Noraxon system showed excellent concurrent validity with the ProtoKinetics system regarding mean step-time, while validity of standard deviation of step-time was poor to fair. Finally, the overall pattern of results was similar within each age group compared to across the entire sample.

Gait Variability Less Reliable than Mean Values

Mean step-time showed excellent reliability within each system, while step-time standard deviation showed fair to good reliability. This discrepancy may be due to the number of steps required to obtain a reliable estimate of *M* versus *SD* estimates. Specifically, only 10 gait cycles are needed to show excellent reliability for mean gait parameters (Hollman et al., 2010; König et al., 2014), whereas 50 gait cycles are needed to achieve reliable results for measurements of gait variability (König et al., 2014). In the current study a median of 42 steps were captured in each trial, approximately 21 gait cycles. The length of each trial was designed to balance research aims and participant burden. Nevertheless, due to the limited number of steps collected, *SD* estimates may not reflect true values which may have impacted reliability estimates.

Gait Variability Different Between Measurement Systems

Mean step-time showed excellent validity between systems while the standard deviation of step-time showed poor to fair validity. While the LoA analyses indicated low mean bias for both mean and standard deviation of step-time, a negative trend was observed in the Bland-

Altman plots for the standard deviation of step-time (see *Figure 3*), which was statistically significant in the *Cued* walking condition. This implies either there is proportional bias such that larger *SD* values are prone to larger measurement error, or, that the mean *SD* of the two measurement systems is a poor substitute for the true *SD* value (Mansournia et al., 2021). As discussed above, it is likely that *SD* estimates in the current study do not reflect the true value given the limited number of gait cycles acquired. It is likely, then, that poorer agreement between systems for the *SD* of step-time relative to the *M* of step-time are due to the limited number of gait cycles captured. This interpretation is supported by the finding that reliability estimates were lower for *SD* of step-time for *both* systems relative to the *M* of step-time, suggesting measurement error in gait variability was not limited to one system. However, we cannot rule out the possibility of true proportional bias. Another reason for the disagreement between measurement systems may be due to differences in sampling rate. The ProtoKinetics Zeno Walkway is sampled at a rate of 120Hz and the Noraxon DTS FootSwitches are sampled at a rate of 1500Hz. The Noraxon system may be more sensitive to small changes in step-time resulting in greater variability in the readings from the Noraxon as compared to the ProtoKinetics system. Rounding differences may also account for some disagreement between the two systems.

The main limitation of this study is the number of steps captured. This has limited our interpretation of estimates of gait variability and their reliability and validity, discussed above. Our reported estimates for reliability and validity of gait variability are also a strength of this study, despite potentially biased *SD* estimates. Authors sometimes conclude that an instrument is reliable and valid tool for the measurement of gait variability based on strong agreement for mean values without reporting on measures of variability (e.g., Beauchet et al., 2008). Overall, our results are in line with guidelines suggesting that more steps are required to produce reliable and valid estimates of gait variability as compared to mean gait parameters.

Age-Related Comparisons

Reliability estimates for the *M* and *SD* of step-time among middle-aged and older adults ranged from good to excellent. Younger adults showed excellent reliability for *M* but fair reliability for *SD* of step-time. The sample size for young adults was quite small ($n = 3$), which may account for the relatively lower reliability among young adults. Regarding validity, step-time *M*s derived from the FootSwitch system showed excellent concurrent validity with values obtained from the criterion ProtoKinetics Zeno Walkway system, across age groups. Step-time

SD showed poor to fair validity and estimates were not statistically significant, across age groups. The only exception to this pattern was among older adults whose step-time *SD* showed excellent validity in the *Cued* condition. This result should not be over-interpreted however given the limited number of steps captured in this study (discussed above). In summary, the pattern of results observed within each age group was similar to the overall pattern of results observed for the entire sample.

Conclusion

The Noraxon DTS FootSwitches are a reliable tool for the assessment of gait and showed excellent concurrent validity when compared with the ProtoKinetics system across age groups. The agreement between the two measurement systems was such that the systems can be considered interchangeable, particularly regarding mean estimates. Estimates of gait variability were less reliable and valid as compared to mean estimates, likely due to the limited number of steps captured in our study. The *SD* of spatiotemporal gait parameters is a sensitive measure of health outcomes such as falls risk and clinicians may be particularly interested in this gait parameter. It is important for clinicians and researchers to be aware of the number of steps required to obtain an accurate and reliable estimate.

Table 1

Reliability estimates (ICC) and 95% CI for step-time M and SD in Uncued *and* Cued *conditions, for the ProtoKinetics and Noraxon DTS FootSwitches systems*

Measurement device	Condition	Gait parameter	ICC	95% CI	p-value
ProtoKinetics	Uncued (*n* = 22)	Step-time mean (ms)	0.964	0.833, 0.988	<.001
	Cued (*n* = 27)		0.983	0.956, 0.933	<.001
	Uncued (*n* = 22)	Step-time *SD* (ms)	0.837	0.647, 0.929	<.001
	Cued (*n* = 27)		0.621	0.33, 0.806	<.001
Footswitches	Uncued (*n* = 22)	Step-time mean (ms)	0.956	0.814, 0.985	<.001
	Cued (*n* = 27)		0.977	0.95, 0.989	<.001
	Uncued (*n* = 22)	Step-time *SD* (ms)	0.587	0.224, 0.806	.002
	Cued (*n* = 27)		0.385	0.014, 0.663	.021

Table 2

Validity estimates (ICC) and limits of agreement (LoA) and their respective 95% CI for step-time M and SD in Uncued *and* Cued *conditions, between the ProtoKinetics and Noraxon DTS FootSwitches systems*

Condition	Gait parameter	ICC	95% CI	p-value	LoA [95% CI]	Upper LoA [95%CI]	Lower LoA [95% CI]
Uncued (*n* = 22)	Step-time mean (ms)	0.999	0.995, 0.999	<.001	1.30 [0.36, 2.23]	5.43 [3.81, 7.05]	-2.83 [-4.46, 1.21]
Cued (*n* = 27)		0.997	0.994, 0.999	<.001	-0.63 [-1.74, 0.47]	4.83 [2.92, 6.73]	-6.09 [-8.00, -4.19]
Uncued (*n* = 22)	Step-time *SD* (ms)	0.234	-0.19, 0.587	.137	-2.38 [-6.89, 2.13]	17.55 [9.72, 25.38]	-22.32 [-30.15, -14.49]
Cued (*n* = 27)		0.4	0.029, 0.674	0.018	-0.98 [-3.75, 1.78)	12.74 [7.94, 17.53]	-14.71 [-19.50, -9.91]

Table 3.

Reliability estimates (ICC) and 95% CI for step-time M and SD in Uncued *and* Cued *conditions, for the Noraxon DTS FootSwitches systems, for young, middle-aged, and older adults*

Age Group	Condition	Gait parameter	ICC	95% CI	p-value
Young adults	Uncued (*n* = 3)	Step-time mean (ms)	0.948	0.006, 0.999	0.023
	Cued (*n* = 6)		0.882	0.458, 0.982	0.002
	Uncued (*n* = 3)	Step-time *SD* (ms)	0.864	-1.299, 0.996	0.095
	Cued (*n* = 6)		0.059	-0.848, 0.791	0.453
Middle-aged adults	Uncued (*n* = 11)	Step-time mean (ms)	0.972	0.905, 0.992	< .001
	Cued (*n* = 12)		0.989	0.894, 0.998	< .001
	Uncued (*n* = 11)	Step-time *SD* (ms)	0.488	-0.141, 0.832	0.058
	Cued (*n* = 12)		0.903	0.71, 0.971	< .001
Older adults	Uncued (*n* = 8)	Step-time mean (ms)	0.952	0.564, 0.991	0.002
	Cued (*n* = 9)		0.981	0.916, 0.996	< .001
	Uncued (*n* = 8)	Step-time *SD* (ms)	0.717	0.058, 0.937	0.019
	Cued (*n* = 9)		0.864	0.505, 0.968	< .001

Table 4.

Validity estimates (ICC) and their 95% CI for step-time M and SD in Uncued *and* Cued *conditions for young adults, middle-aged adults, and older adults, between the ProtoKinetics and Noraxon DTS FootSwitches systems*

Age group	Condition		ICC	95% CI	p-value
Young adults (*n* = 3)	Uncued	Step-time mean (ms)	1	0.997, 1	<.001
	Cued		0.987	0.907, 0.998	<.001
	Uncued	Step-time *SD* (ms)	0.413	-1.413, 0.981	0.301
	Cued		0.449	-0.235, 0.889	0.103
Middle-aged adults (*n* = 12)	Uncued	Step-time mean (ms)	0.997	0.976, 0.999	<.001
	Cued		0.996	0.987, 0.999	<.001
	Uncued	Step-time *SD* (ms)	0.064	-0.342, 0.56	0.395
	Cued		0.045	-0.598, 0.602	0.446
Older adults (*n* = 9)	Uncued	Step-time mean (ms)	1	0.998, 1	<.001
	Cued		1	1, 1	<.001
	Uncued	Step-time *SD* (ms)	0.435	-0.341, 0.855	0.122
	Cued		0.773	0.309, 0.943	0.003

Figure 1

Schematic of Data Acquisition for Experimental Set-Up

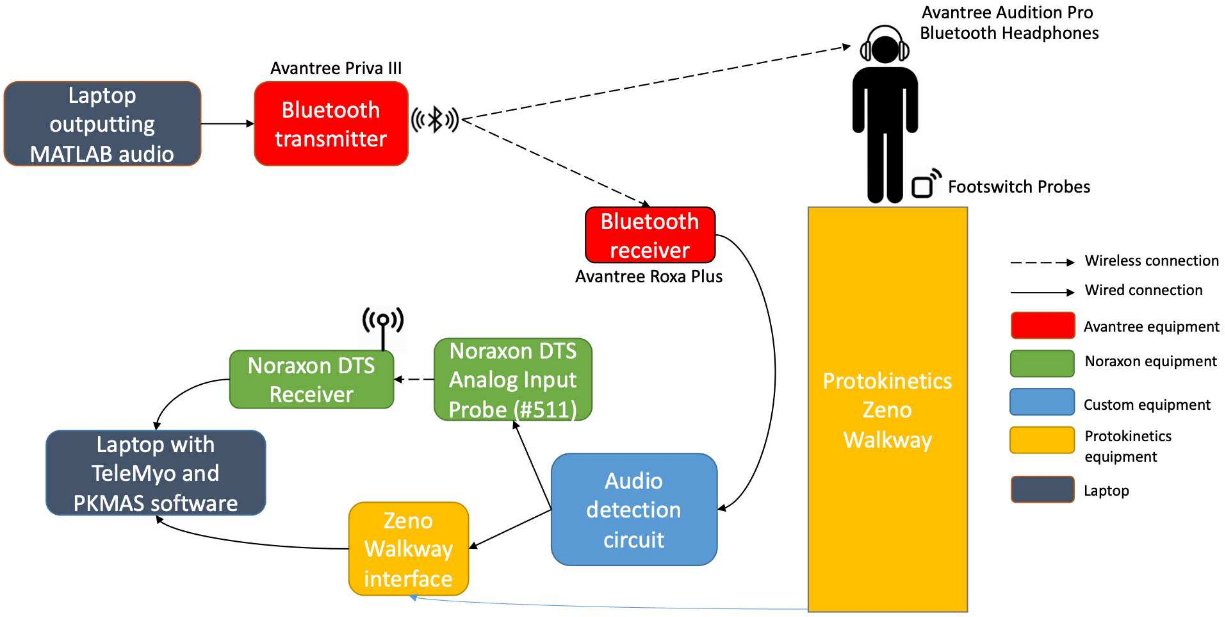
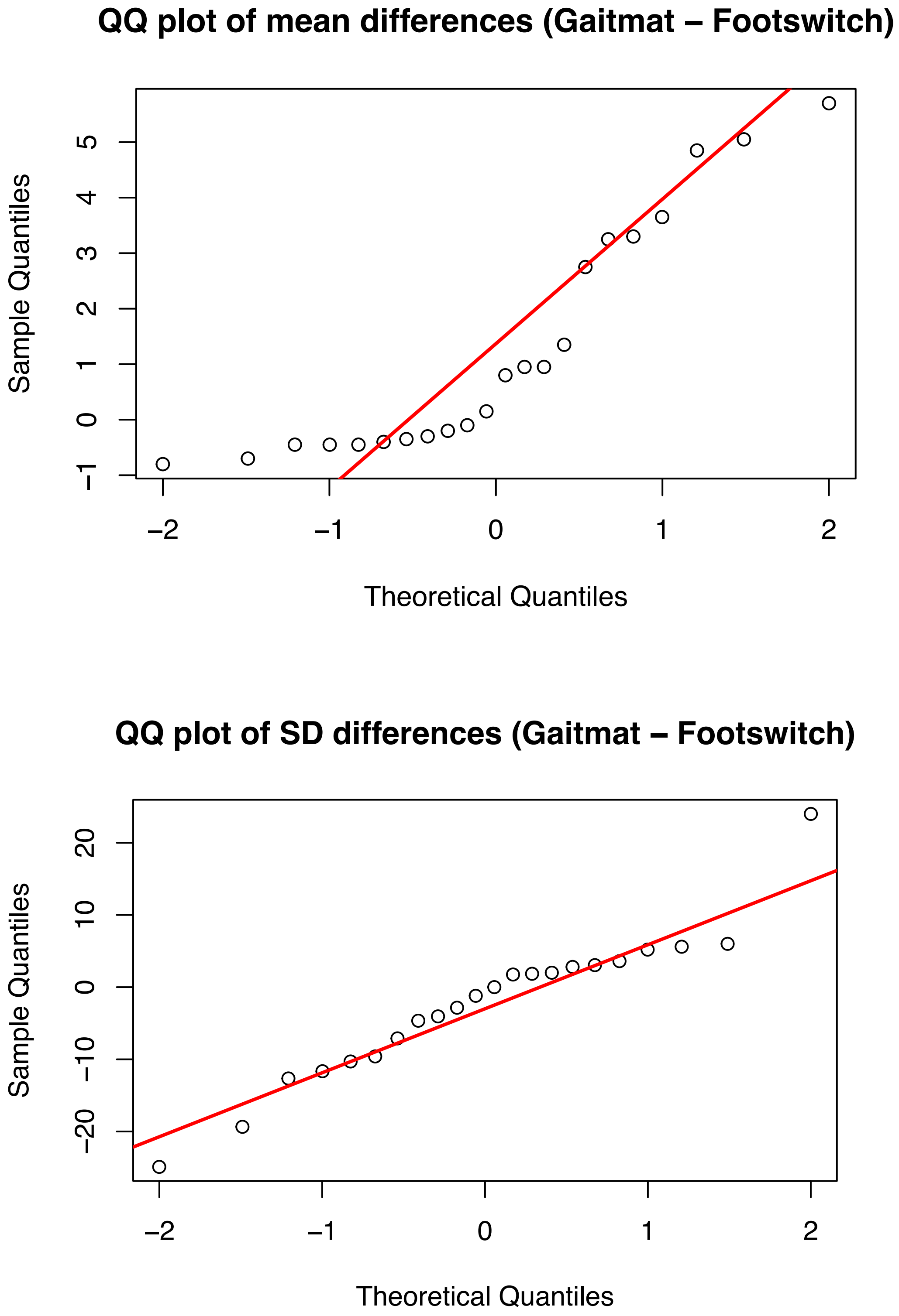


Figure 2

Quantile-Quantile Plots for Differences of Ms and SDs Between Measurement Devices

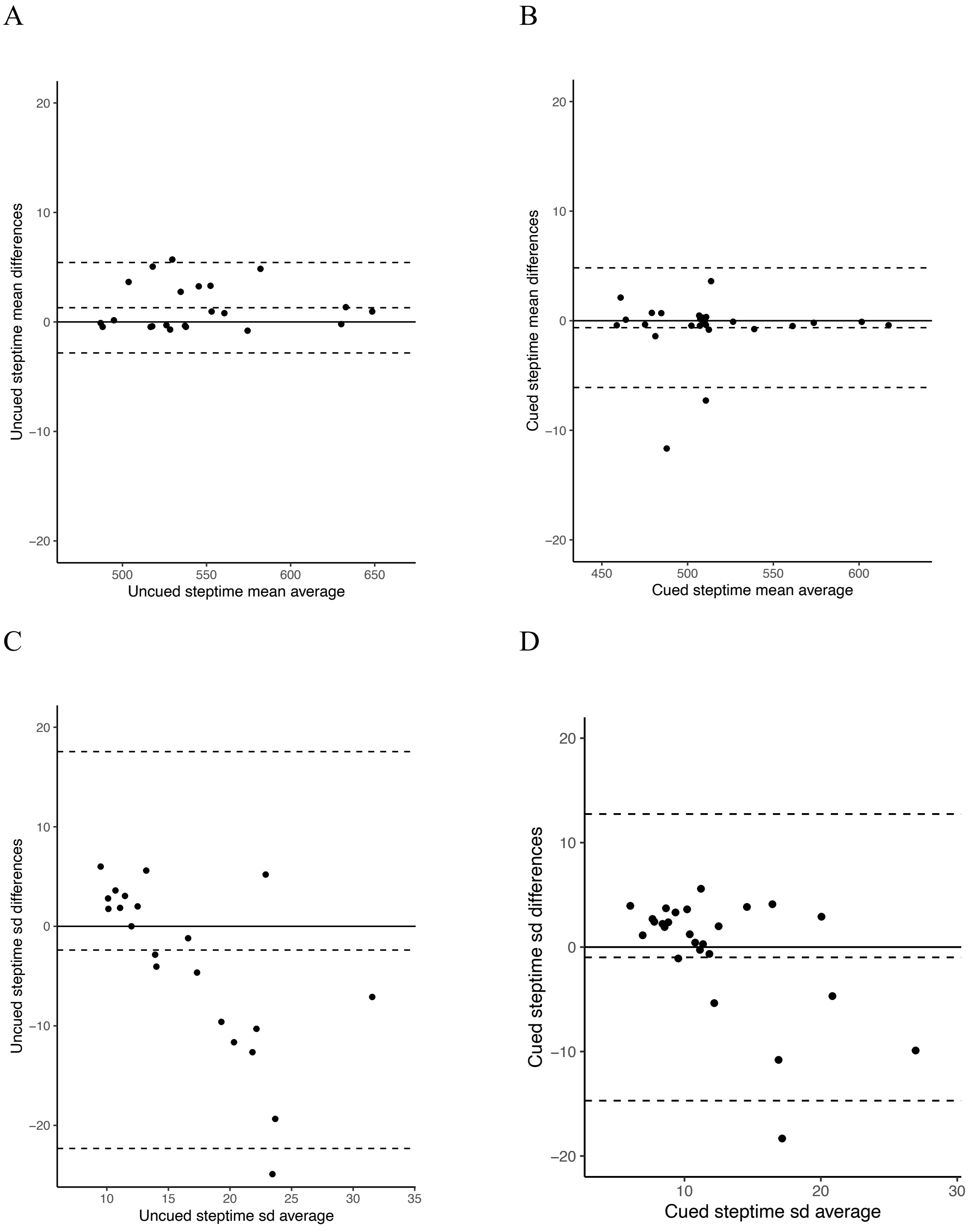


QQ plot of mean differences (Gaitmat – Footswitch)

QQ plot of SD differences (Gaitmat – Footswitch)

Figure 3

Bland-Altman Plots



Note. Bland-Altman plots for Uncued (A) and Cued (B) step-time mean, and Uncued (C) and Cued (D) step-time standard deviation

CHAPTER 3: Walking to a beat is modulated by task complexity and individual differences in age, beat perception, and selective attention

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 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, 2024). 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).

Materials and Procedure

Participants completed two in-person sessions on separate days, each lasting 2 – 2.5 hours. 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 meters, 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 seconds 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 (MathWorks, 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 meters wide and 9.07 meters 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} = (dual-task_{CoV} – single-task_{CoV})/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).

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 *Figure 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 ($\beta = 0.59$, *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 *Figure 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 ($\beta = -0.24$, *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 *Figure 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 ($\beta = -0.22$, *SE* = 0.08). This result supports hypothesis 4, that those with greater selective auditory attention will benefit more from cued walking.

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 ($\beta = 0.28$, *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, 2024). 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 did not 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 to 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

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

Table 2

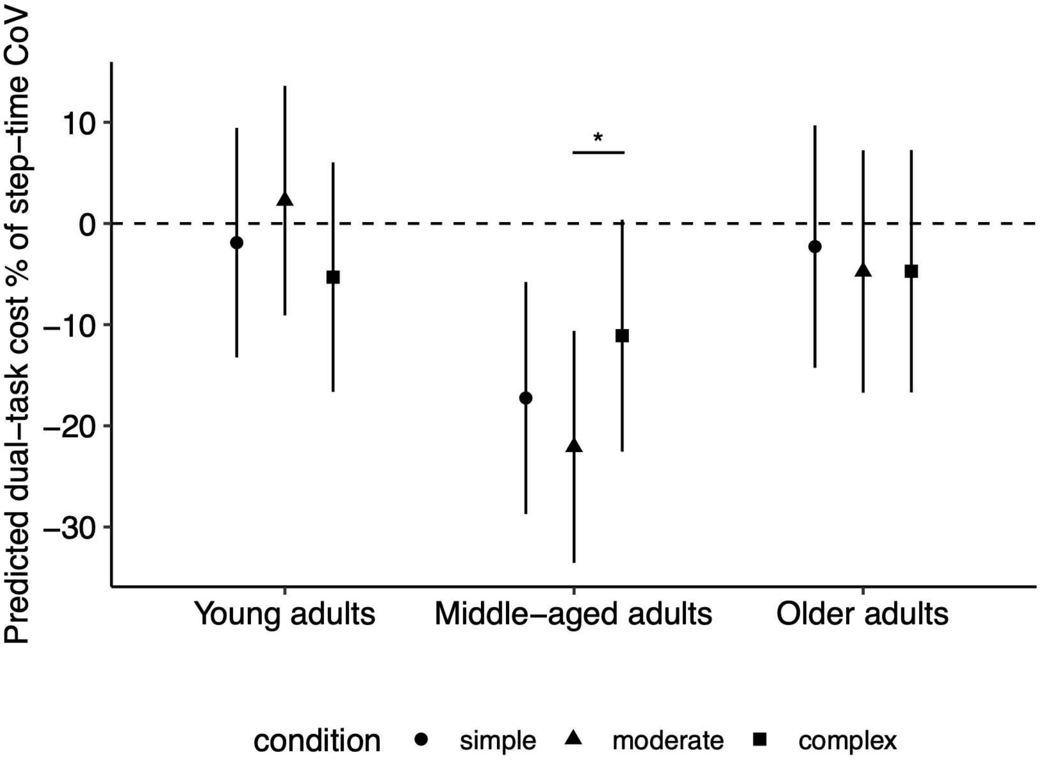
Step-time CoV% for Each Walking Condition for Young, Middle-Aged, and Older Adults

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)

Note. ST = single task, DT = dual task

Figure 1

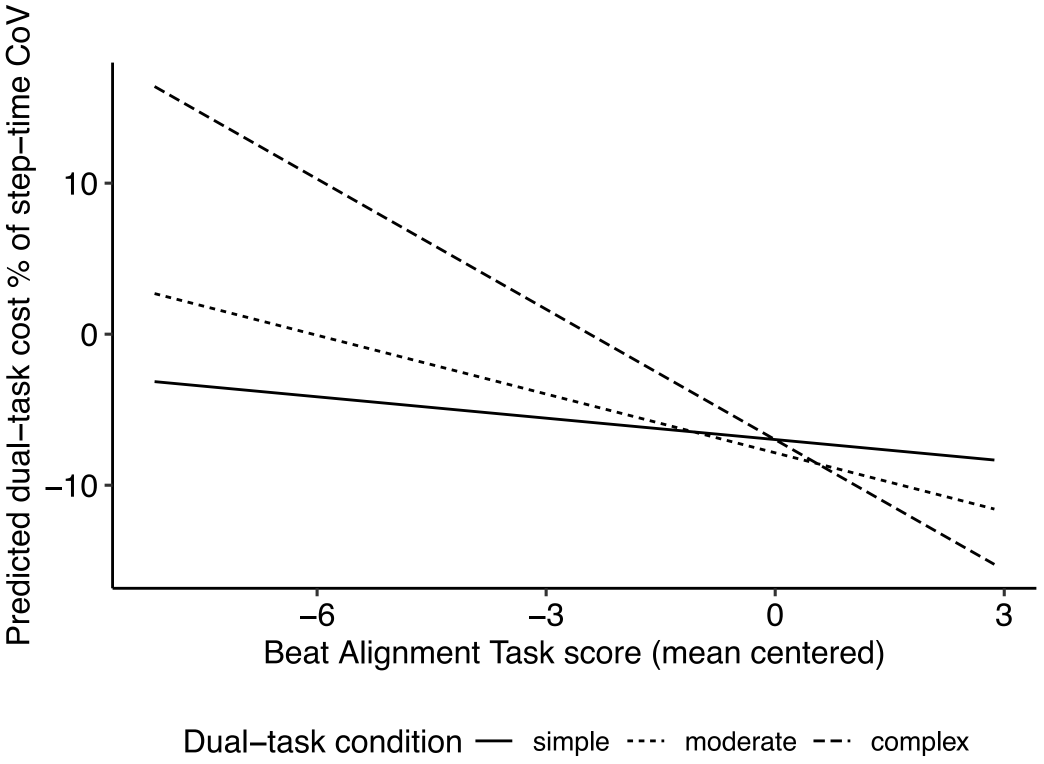
Dual-Task Cost% in Step-Time CoV by Age Group and Condition



Note. 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

Figure 2

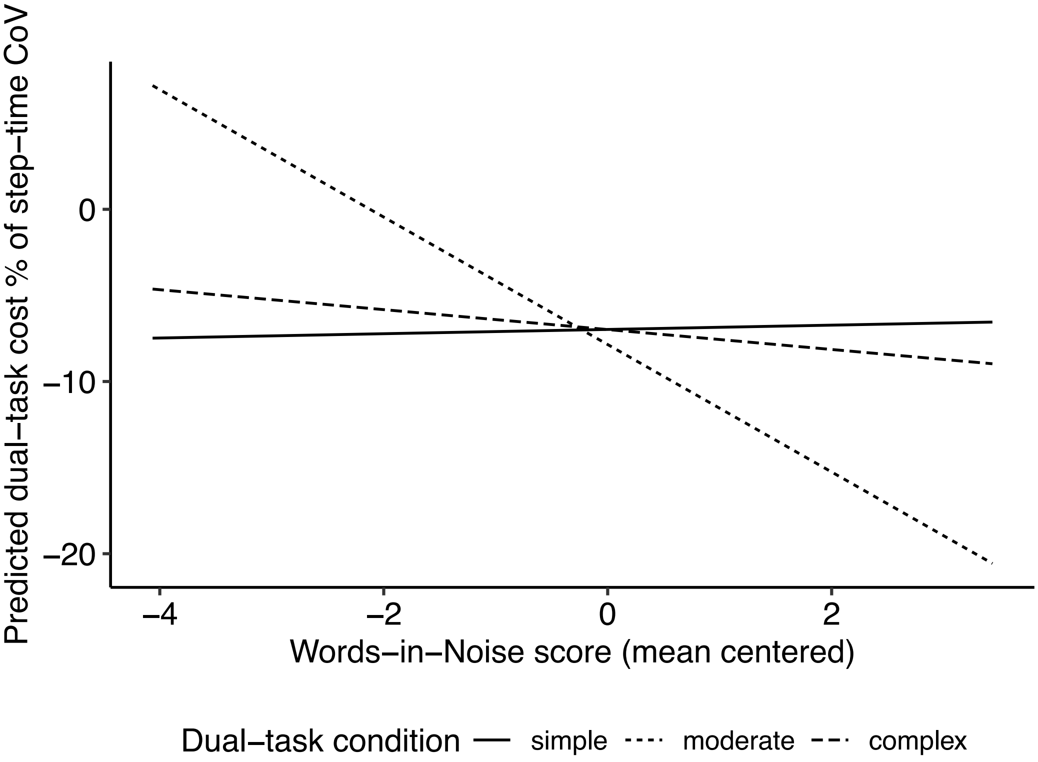
Association Between Beat Alignment Task and DTC in Step-Time CoV%



Note. 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

Figure 3.

Association Between the Words-in-Noise Task and DTC in Step-Time CoV%



Note. 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

Supplementary Information 1

Table A presents the mean scores (with standard deviations) for each age group on additional measures administered during Session 1 testing.

Table A

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
Digit Span total (/48)	29.50 (4.51)	27.80 (4.70)	30.25 (5.66)	.28	.04
Letter Number Sequencing total (/30)	20.00 (1.77)	19.55 (2.26)	19.45 (1.61)	.60	.02
Stroop inhibition (3 - 1, sec.)	14.60 (5.74)$^{\$}$	19.52 (9.33)	22.28 (7.26)*	.01	.16
Stroop switching (4 - 3, sec.)	8.80 (10.92)$^{+}$	-0.22 (9.61)*	4.46 (11.05)	.03	.11
Goldsmiths General Musical Sophistication (range 18 - 126)	65.36 (17.35)	69.10 (21.56)	64.15 (20.97)	.72	.01

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

Supplementary Information 2

Model fitting procedure

Model 1, walking performance

Random effects: participant ID was added as a random effect. Adding walking direction nested within participant as a random effect significantly improved model fit compared to a random intercept model for % change step-time CoV (χ^2 (1) = 22.28, p < .001*)*. Order of conditions did not significantly improve model fit and was therefore removed from subsequent models (χ^2 (1) = 0.00, p = 1*)*. Participant Cadence did not significantly improve model fit and was therefore removed from subsequent models (χ^2 (1) = 0.50, p = 0.478).

Fixed effects: We hypothesized an age group by condition interaction. Age group and condition did not significantly improve model fit when added separately (*p*s < .05), however model fit was improved by adding age group and condition as well as their interaction (χ^2 (8) = 15.72, p = .047). Adding Words-in-Noise task performance (a measure of auditory selective attention) as well as it's interaction with condition significantly improved model fit (χ^2 (3) = 9.44, p = .024). Adding Beat Alignment Task performance (a measure of beat perception) as well as it's interaction with condition significantly improved model fit (χ^2 (3) = 12.74, p = .005). Adding musical sophistication score, Digit Span score, Letter Number Sequencing score , Stroop inhibition cost, or Stroop switching cost did not improve model fit (*p*s > .05), and therefore these were not retained in the final model. The final model is as follows:

DTC step-time CoV ~
(age group + auditory selective attention + beat perception) * condition + (1 | ID) +
(1 | direction:ID)

Model 2, auditory monitoring task performance

Random effects: participant ID was added as a random effect. Order of conditions did not significantly improve model fit and was therefore removed from subsequent models (χ^2 (1) = 0.00, p = 1). Participant Cadence did not significantly improve model fit and was therefore removed from subsequent models (χ^2 (1) = 0.074, p = .786).

Fixed effects: Age Group significantly contributed to model fit (χ^2 (2) = 6.00, p = .0498*)*. Load and the interaction between Load and Age Group did not contribute significantly to model fit ($p > .05$) and were therefore not included in the final model. MoCA score significantly contributed to model fit (χ^2 (1) = 4.858, p = .028). The final model is as follows:

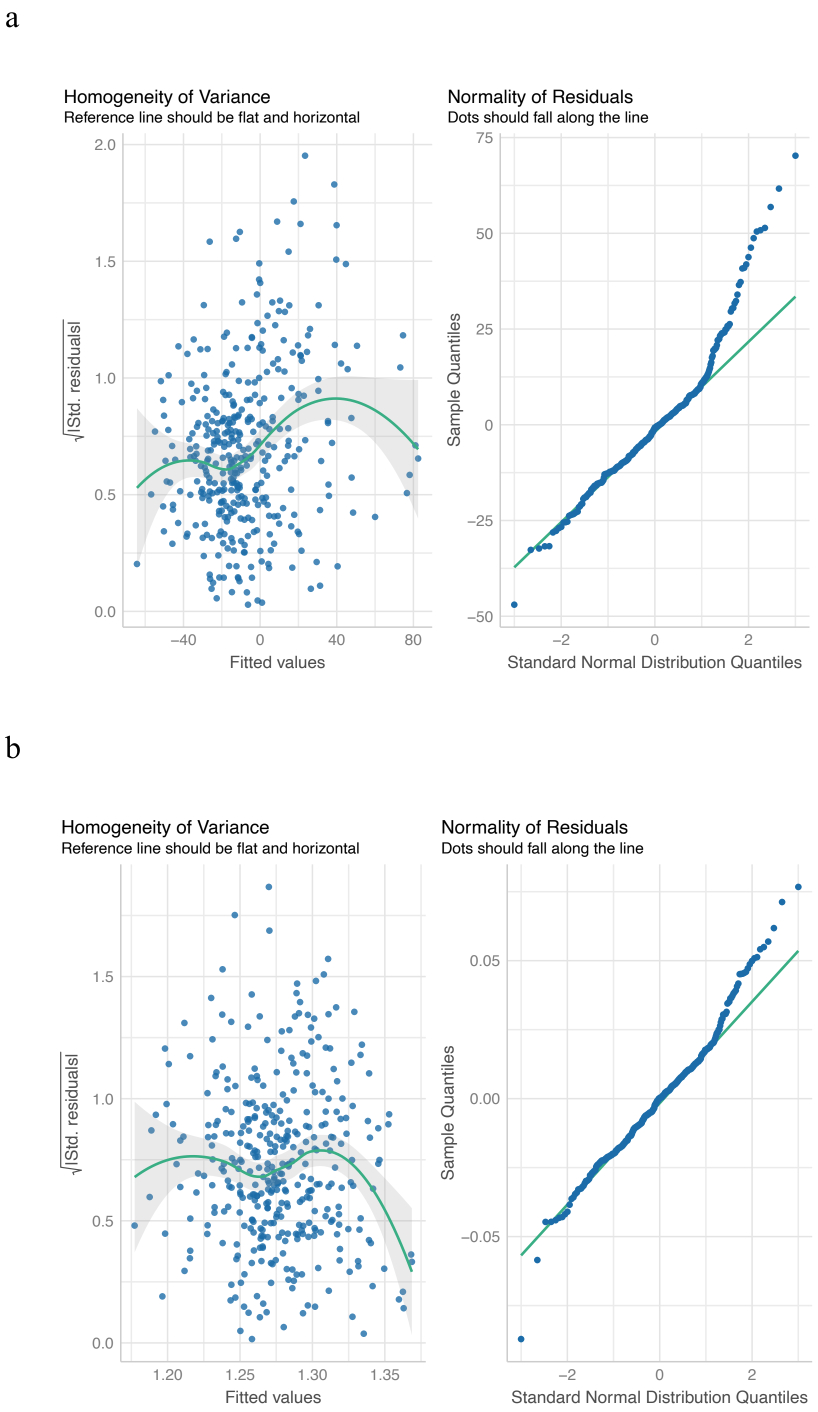
Hits minus false alarms ~
    Age Group + MoCA + (1 | ID)

Inspection of dependent variables

Each dependent variable was visually inspected for homogeneity of variance and normality of residuals. For DTC in step-time CoV, slight right skew was observed (see *Figure A1*). The lambda value derived from the Box-Cox method in R (Fox & Weisberg, 2011) indicated a negative power transformation ($\lambda = -0.69$, $p < .001$), which improved the normality of residuals (see *Figure A1*). However, when the model effects were examined, the untransformed and the transformed models yielded the same results. Therefore, for ease of interpretation, the untransformed values were reported in the current manuscript. For hits minus false alarms a slight right and left skew was observed (see *Figure A2*). However, the lambda value derived from the Box-Cox method in R was not statistically significantly different from 1, indicating that no power transformation was needed ($\lambda = 0.994$, p = . 970).

Figure A1

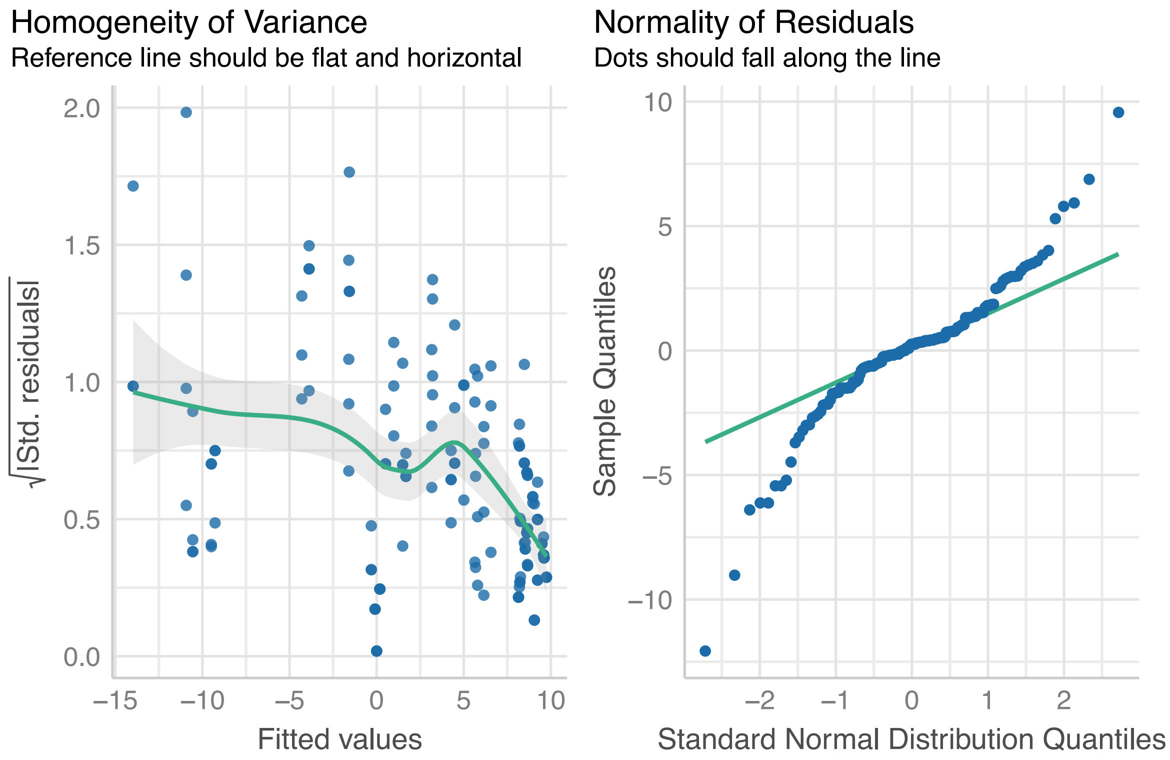
Visual Inspection of Model 1 Assumptions for Untransformed and Transformed Data



Visual representation of homogeneity of variance and normality of residuals of % change in step-time CoV before (a) and after (b) transformation

Figure A2

Visual Inspection of Model 2 Assumptions



Note. Visual inspection of homogeneity of variance and normality of residuals for hits minus false alarms revealed that residuals were not severely non-normal nor heteroscedastic

CHAPTER 4: Tuned to Walk: Cue Type, Beat Perception, and Gait Dynamics During Rhythmic Stimulation in Aging

Walking to external auditory cues, termed Rhythmic Auditory Stimulation (RAS), is an intervention for gait rehabilitation which improves spatiotemporal gait parameters in healthy older adults (Ghai et al., 2018). However, previous studies investigating RAS 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 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 RAS. 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 RAS (Cochen de Cock et al., 2018). Across research investigating RAS 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 – 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 fallers as compared to non-fallers (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 & 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 RAS

Walking to regular auditory cues is an empirically supported intervention for gait rehabilitation among healthy older adults (Ghai et al., 2018). Many studies investigating RAS use an auditory stimulus with an isochronous rhythm (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 & 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 RAS, 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 & 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 & 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). However, these studies did not include rhythmic auditory cueing stimuli.

There is a dearth of research investigating the impact of attentional load on the long-range correlations of gait during RAS. Researchers have speculated as to how dual tasking may impact gait during RAS generally (Peterson & Smulders, 2015). RAS may reduce the attentional load required for timing steps and maintaining stable gait and result in lower dual-task costs during RAS compared to dual-tasking without RAS. Or, the instruction to synchronize one's steps to external auditory cues may focus attention on gait resulting in prioritization of gait over performance on a secondary task. Alternatively, synchronizing steps to cues may add an additional cognitive load while walking, leading to greater dual-task costs relative to when walking in silence.

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. Researchers have speculated as to how RAS may moderate the relationship between walking performance and attentional load. Empirical work investigating manipulations of attentional load during RAS and considering the temporal structure in gait is lacking.

Individual Differences in Response to RAS

There is evidence that individuals vary in their response to RAS and studying these individual differences can further our understanding of the mechanisms of RAS. Those with better beat perception and who are better able to synchronize their steps to rhythmic cues benefit more from cued walking (Cochen De Cock et al., 2018). Consistent with these findings, researchers have proposed that benefit to gait during RAS 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 RAS (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, Dalla Bella, Penhune, Young, & Li, in press). Little is known regarding how beat perception ability interacts with the temporal structure of cues. Possibly, those with poor beat perception will be disadvantaged under both fractal and isochronous cueing conditions, given that synchronizing steps to tones is more cognitively demanding for this group. The current study aims to examine 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 RAS 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 correlation in gait across the adult lifespan. The second aim is to examine the role of attention during RAS 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 RAS. 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; 3) those with better beat perception would show a higher fractal scaling exponent (α) across cue-types relative to those with poorer beat perception.

Method

Participants

Participants and further details on the protocol have been described more fully elsewhere (Parker, Dalla Bella, Penhune, Young, & Li, in press). 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 & Yesavage, 1986), see *Table 1*. This project received approval from the University Human Research Ethics Committee of Concordia University.

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 hours.

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 <

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

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

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 & 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 & 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 & Patel, 2008), a subtest from the Battery for the Assessment of Auditory and Sensorimotor Timing Abilities (BAASTA; Dalla Bella et al., 2017a, 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 auditory 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 meters wide and 9 meters 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 x 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 ($\text{change}_{\alpha} = \text{cued}_{\alpha} - \text{uncued}_{\alpha}$), 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:

$$\begin{aligned} Change\ in\ Fractal\ Scaling\ Exponent\ (\alpha) \sim\ & Cue\ Type * (Age\ Group + Beat\ Perception) \\ & + Uncued\ Fractal\ Scaling\ Exponent\ (\alpha) \\ & + (1 \mid ID) \\ & + (1 \mid WalkingDirection{:}ID) \end{aligned}$$

$$\begin{aligned} Hits\ Minus\ False\ Alarms \sim\ & Attentional\ Load\ *\ Age\ Group \\ & + (1 \mid ID) \end{aligned}$$

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. 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* < .001, see *Figure 1*, with a main effect of Cue Type, *F*(1, 616.00) = 45.63, *p* < .001, and no main effect of Age Group, *F*(2, 76.03) = 2.11, *p* = .13. Post-hoc tests were performed against

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

Note. LT = Low tones, HT = Hight tones

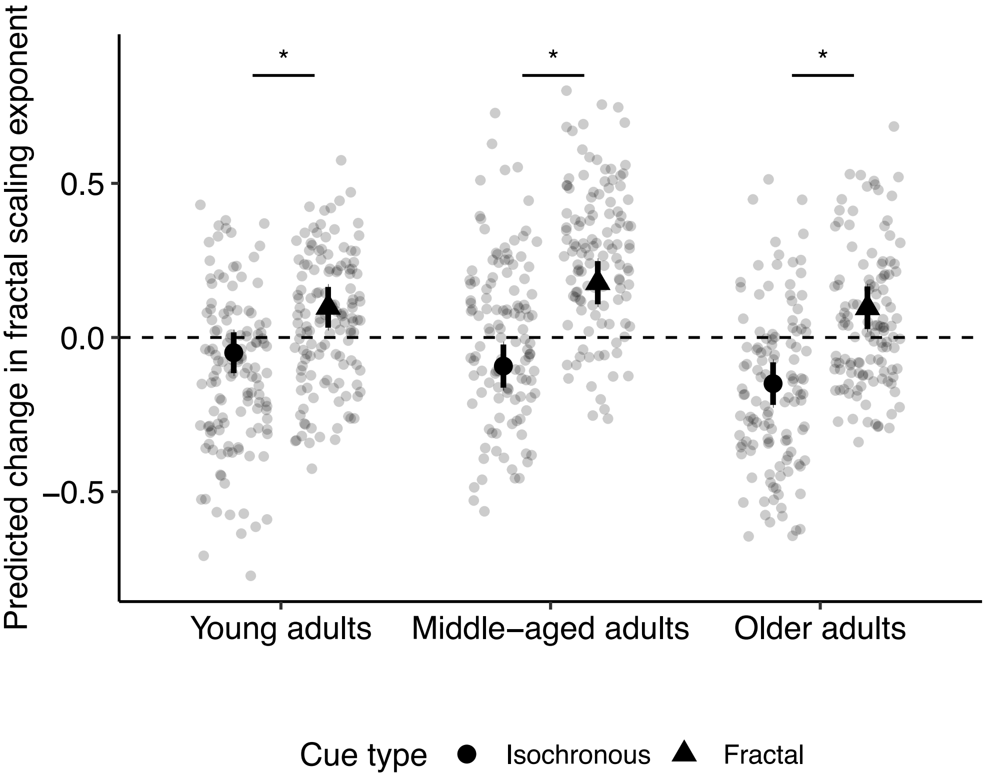


Fig. 1 Estimated change in the fractal scaling exponent (α) by cue type and age group. Walking to fractal cues resulted in a higher fractal scaling exponent relative to walking to isochronous cues, particularly for middle-aged adults. Estimated marginal means are displayed as large shapes, error bars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

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 < .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 the fractal scaling exponent (α) was observed when walking to isochronous cues relative to uncued walking among middle-aged (*m* = -0.09, *p* = .01) and older adults (*m* = -0.15, *p* < .001), but not young adults (*m* = -0.05, *p* = .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* < .001, and a statistically significant interaction between Beat Perception and Cue Type, *F*(1, 616.00) = 35.37, *p* < .001, see *Figure 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* < .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). This result does not support our third prediction, that those with better beat perception would benefit more from cued walking. In contrast, when walking to isochronous cues, better beat perception was associated with less persistent long-range correlations in gait.

There was a main effect of Uncued Fractal Scaling Exponent (α), *F*(1, 101.97) = 97.12, *p* < .001, such that lower Uncued Fractal Scaling Exponent (α) values at baseline (i.e., less persistent long-range correlations in gait) were 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* = .02, see *Figure 3*, with no main effect of Attentional Load, *F*(1, 256.62) =

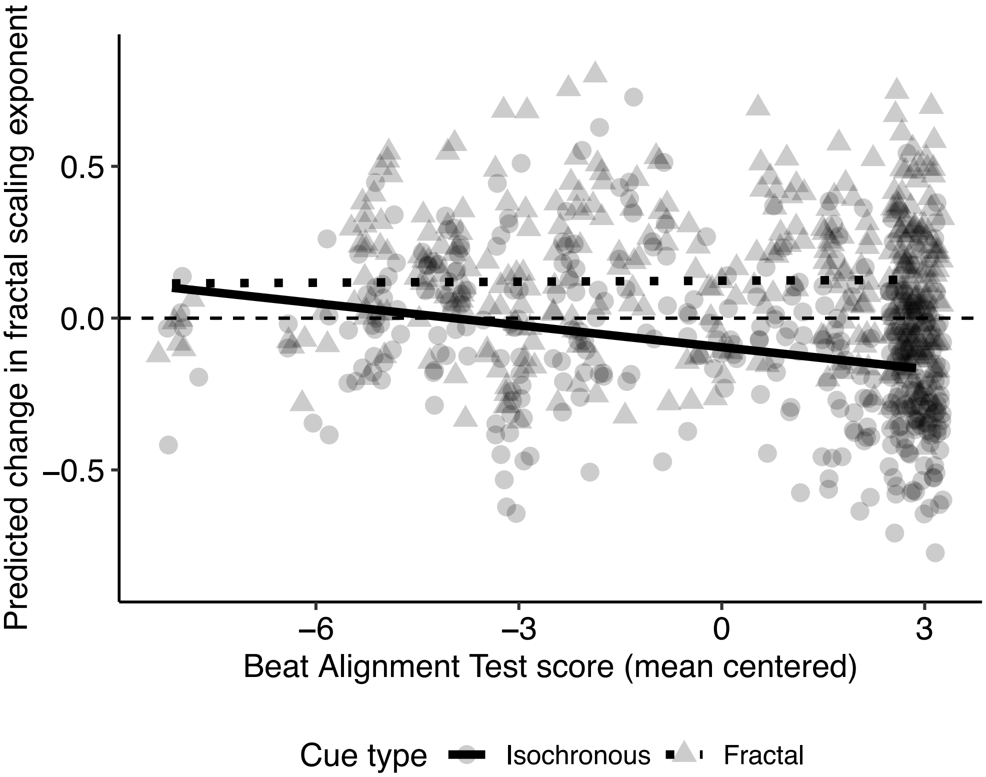


Fig. 2 Change in the fractal scaling exponent (α) by cue type and beat perception. Increasing beat perception score was associated with decreasing fractal scaling exponent (α) while walking to isochronous cues (solid line). No relation was observed when walking to fractal cues (dotted line). Raw α values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

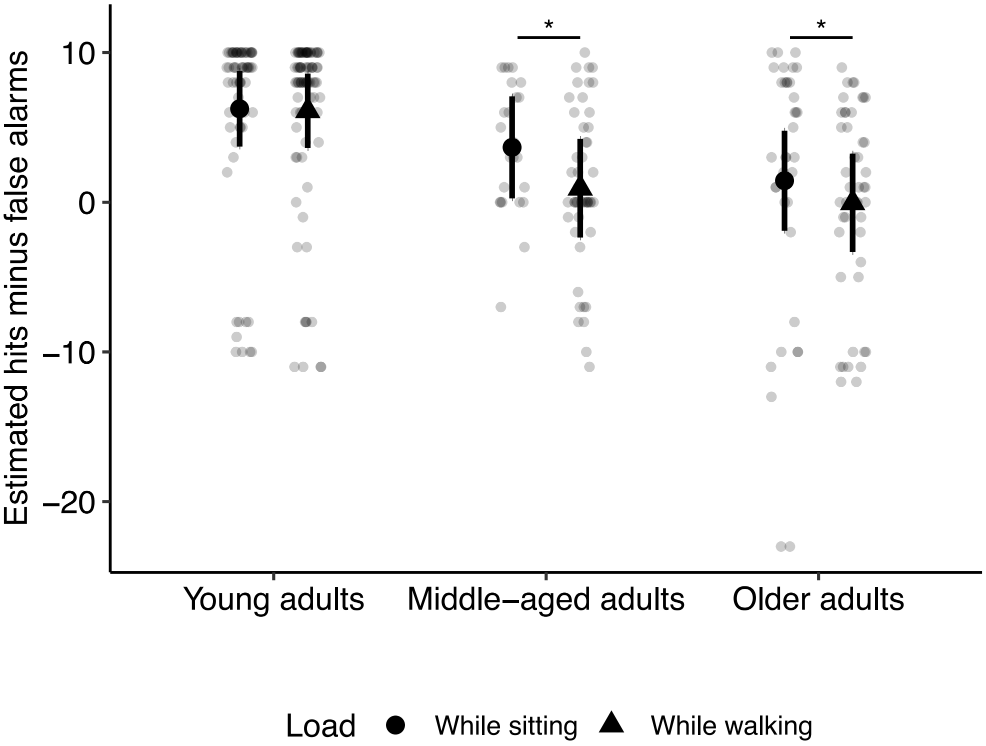


Fig. 3 Performance on the auditory monitoring task by attentional load and age group**.** Middle-aged adults and older adults showed a cost to performance in the auditory monitoring task while walking compared to while sitting. Young adults maintained task performance across conditions of attentional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

0.07, $p = .79$, nor of Age Group, $F(2, 48.39) = 2.64$, $p = .08$. Post-hoc contrasts showed that middle-aged and older adults performed significantly worse on the auditory monitoring task while walking compared to while sitting ($m_{\text{diffMA}} = -2.73$, $p < .001$; $m_{\text{diffOA}} = -1.48$, $p = .03$), while young adults showed no costs to monitoring performance when walking compared to sitting ($m_{\text{diffYA}} = 0.14$, $p = .79$).

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 RAS in older and middle-aged adults. We investigated the impact of these factors on the temporal structure of gait during RAS 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 benefitted the temporal structure in gait in healthy adults across the lifespan resulting in increased α values relative to uncued walking. This benefit was qualitatively greater among middle-aged adults compared to other age groups. Second, attentional load did not alter the temporal structure of gait. Third, beat perception did not confer an advantage when walking to fractal auditory cues. Contrary to our prediction, 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 a cost to the temporal structure of gait. This finding has potential clinical implications for gait rehabilitation. For example, if a patient's goal is to restore the stride-to-stride fluctuations in their gait, then an isochronous stimulus would be counter-indicated.

Age-Related Differences in Response to RAS

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 benefit 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 RAS. 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 RAS 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 & 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., 2014a). However, some researchers have proposed α values close to 0.75 represents an optimal balance between stability and adaptability (Rhea & 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 minutes in length, while previous studies have used trials of 10 minutes in length (e.g., Kobsar et al., 2014a), 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 & 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 RAS

Contrary to our prediction, increasing the attentional load during RAS 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 RAS 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., 2012a). 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 *Figure 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 & 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 interreference, 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 RAS interventions with minimal cognitive load to avoid interference effects.

Beat Perception Exaggerated the Response to RAS

Contrary to our prediction, we did not find an association between better beat perception scores and benefit to RAS when walking to fractal auditory cues. Our inability to detect a benefit for those with better beat perception may be related to differences in the distribution of beat perception scores in our sample. Previous studies showing an advantage for good beat perceivers have reported bimodally distributed beat perception scores (Ready et al., 2019), or a median score of 68% (Roberts et al., 2021). 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 RAS (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 a less organized temporal structure of 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 RAS 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 come at a cost to the temporal structure of gait, particularly for good beat perceivers. Those with better beat perception may stand to benefit the most from an appropriate match between cue type and target outcome and may also be more prone to harmful effects of an inappropriate cue type-target outcome pairing. 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.

Supplementary Information

Title: Tuned to Walk: Cue Type, Beat Perception, and Gait Dynamics During Rhythmic Stimulation in Aging
Journal: Experimental Brain Research

Model fitting procedure

Walking Performance

Random effects: Participant ID was added as a random effect. Adding Walking Direction nested within Participant ID as a random effect significantly improved model fit compared to a random intercept model ($\chi^2(1) = 17.05$, $p < .001$).

Fixed effects: Cue Type significantly improved model fit for change in fractal scaling exponent ($\chi^2(1) = 226.41$, $p < .001$). Adding Age Group significantly improved model fit ($\chi^2(2) = 16.31$, $p < .001$), as did an interaction between Age Group and Cue Type ($\chi^2(2) = 9.54$, $p = .008$). However, adding Condition alone or in an interaction with Age Group did not improve model fit (*ps* > .05). Thus, Condition and its interaction with Age Group were not included in the final model. Adding Uncued Fractal Scaling Exponent (α), significantly improved model fit ($\chi^2(1) = 62.09$, $p < .001$). Adding Beat Perception as well as it's interaction with Cue Type significantly improved model fit ($\chi^2(2) = 38.28$, $p < .001$). The final model is as follows:

$$\begin{aligned} Change\ in\ Fractal\ Scaling\ Exponent\ (\alpha) \sim\ & Cue\ Type * (Age\ Group + Beat\ Perception) \\ & + Uncued\ Fractal\ Scaling\ Exponent\ (\alpha) \\ & + (1 \mid ID) \\ & + (1 \mid WalkingDirection{:}ID) \end{aligned}$$

Auditory Monitoring Task Performance

Random effects: for hits minus false alarms, adding Trial nested within Participant ID as a random effect did not significantly improve model fit compared to a random intercept model (p < .05), and therefore this effect was not included in the final model.

Fixed effects: we hypothesized an Age Group by Attentional Load (sitting vs walking) interaction. Attentional Load ($\chi^2(1) = 8.71$, $p = .003$), Age Group ($\chi^2(2) = 8.37$, $p = .015$), and their interaction ($\chi^2(2) = 8.10$, $p = .017$) all significantly contributed to model fit. Cue Type and Beat Perception did not significantly contribute to model fit (*p*s > .05) and these effects were therefore not included in the final model. The final model is as follows:

$$Hits\ Minus\ False\ Alarms \sim Attentional\ Load\ *\ Age\ Group \\ + (1 \mid ID)$$

Inspection of Dependent Variables

Each dependent variable was visually inspected for homogeneity of variance and normality of residuals. Visual inspection of homogeneity of variance and normality of residuals for change in the fractal scaling exponent (α) revealed that residuals were not severely non-normal nor heteroscedastic (see *Supplementary Figure A1*). The distribution of residuals for hits minus false alarms was heavy-tailed (see *Supplementary Figure A2*). However, the lambda value derived from the Box-Cox method in R was not statistically significantly different from 1, indicating that no power transformation was needed ($\lambda = 1.02$, $p = 0.86$).

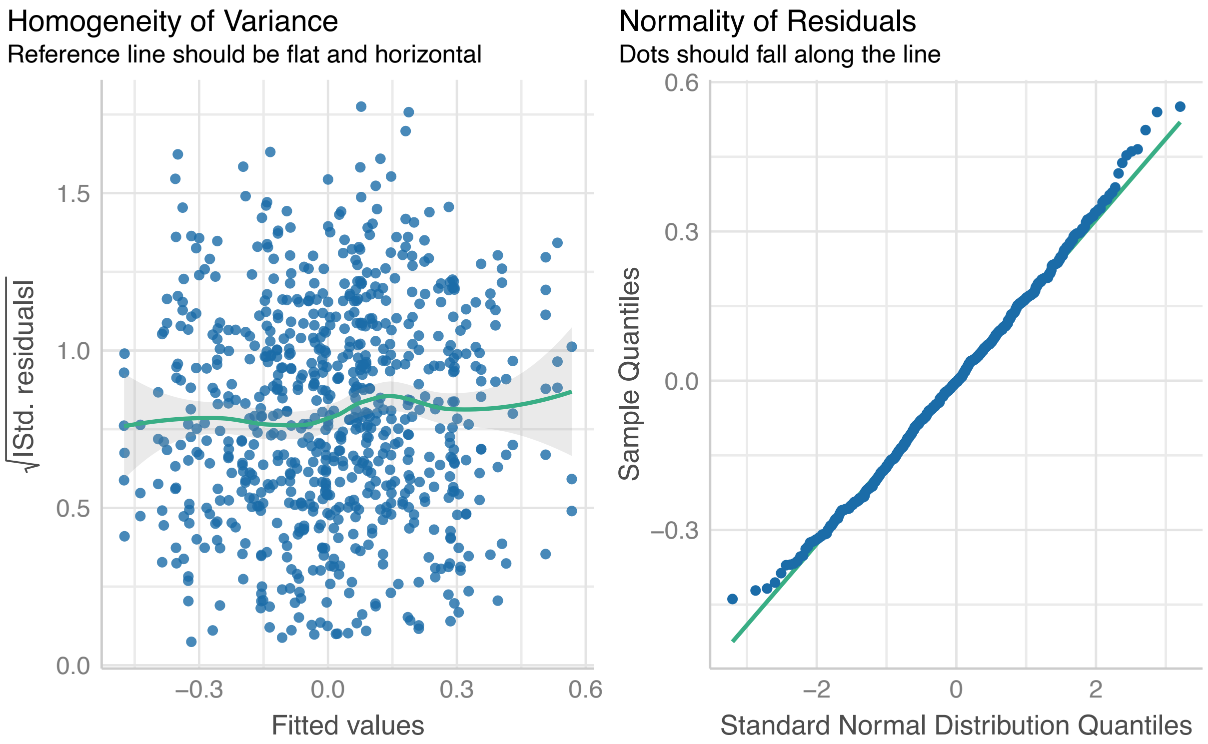


Fig. A1 Homogeneity of variance and normality of residuals for change in the fractal scaling exponent (α)

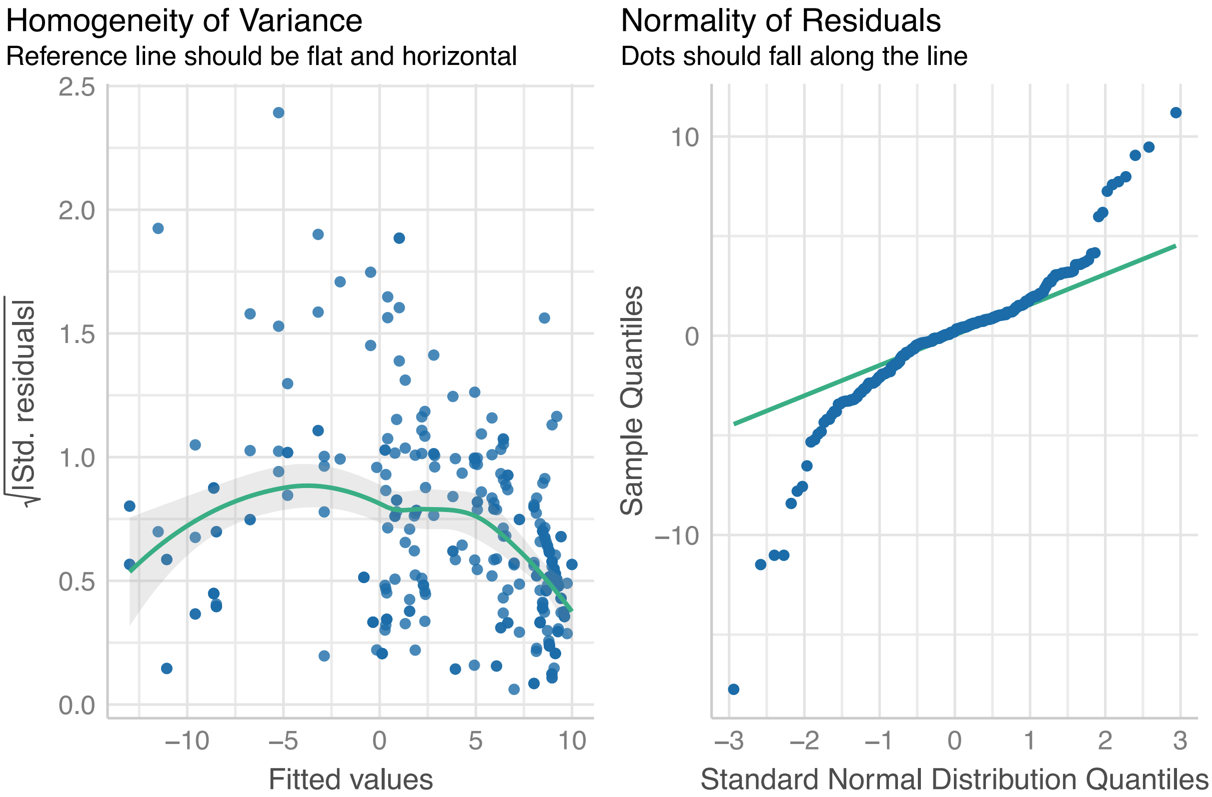


Fig. A2 Homogeneity of variance and normality of residuals for hits minus false alarms

CHAPTER 5: General Discussion

This program of research aimed to clarify the role of attention during RAS with the goal of optimizing RAS for the rehabilitation of gait among older adults. RAS can be an effective intervention to improve gait; however not all individuals benefit. It is therefore critical to better understand the factors which can lead to beneficial or deleterious effects on gait during RAS. Researchers have proposed that synchronizing steps to tones is cognitively demanding (Leow et al., 2018). While it is known that older adults use more attentional and executive resources during walking compared to younger adults (Yogev-Seligmann et al., 2008), the consequences of this for RAS have not been well-described. To address this gap, we sought to clarify the attentional demands of RAS and their impact on gait variability. Gait variability is a particularly sensitive predictor of future falls among older adults (Verghese et al., 2009) and therefore was the parameter of interest in the current research program.

Paper 1 was designed to assess the reliability and validity of a laboratory footswitch system. Footswitches attach to the heel and toe of the shoe or foot and can capture continuous walking data, which facilitates the measurement of gait variability and temporal dynamics in gait--key outcomes of this research program. Paper 2 applied an experimental dual-task design to investigate the impact of increasing attentional load on gait variability as defined by the CoV of step-time. Attentional and perceptual abilities in relation to task performance were also examined. In Paper 3, we applied the same experimental design to determine whether the temporal structure of auditory cues interacted with attentional load or with individual rhythmic perceptual ability to influence temporal dynamics (i.e., naturalistic variability) of gait.

Summary of Findings

Paper 1

In Paper 1 young, middle-aged, and older adults completed walking trials of approximately two minutes while wearing footswitches and concurrently walking on an overground electronic walkway. Participants walked in silence (i.e., *Uncued* condition) and while walking to a series of isochronous tones (i.e., *Cued* condition). Participants completed two trials per condition, which were used to estimate immediate reliability of step-time mean and standard deviation using intra-class correlations (ICC). The concurrent validity of step-time mean and standard deviation obtained from the footswitches against the criterion electronic walkway was estimated using ICCs and 95% Limits of Agreement (LoA). Mean step-time displayed excellent reliability for both instruments, while the standard deviation of step-time was fair to good. The footswitch system showed excellent validity regarding mean step-time while the standard deviation of step-time showed poor to fair validity. The LoA were narrower, indicating higher agreement, for mean step-time values as compared to step-time standard deviation values. Mean bias was low for mean and standard deviation of step-time, though a negative trend was apparent in the Bland-Altman plots for the standard deviation of step-time. Reliability and validity estimates for mean step-time were excellent when separated by age group. Similar to the pattern that emerged across the entire dataset, reliability and validity estimates were lower for the standard deviation of step-time within each age group.

Paper 2

In Paper 2, 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*). The outcome measure for the walking task was dual-task cost% of step-time CoV%, a measure of gait variability. Middle-aged adults improved their walking in the *Simple* condition relative to walking in silence and this benefit was attenuated in the *Complex* condition. As a group, young and older adults showed no changes to walking under dual-task conditions. Post-hoc analyses showed that a subgroup of older adults benefitted in the *Simple* condition. Older adults who benefitted in the *Simple* condition were more likely to have poorer motor performance at baseline. 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. There were no differences in performance on the auditory monitoring task between sitting and walking conditions, for any age group.

Paper 3

In Paper 3 young, middle-aged, and older adults walked around an elliptical track in silence and in three cued walking conditions of increasing attentional load. Auditory cues had a temporal structure with either isochronous (i.e., with an evenly spaced inter-beat interval) or fractal (i.e., with an inter-beat interval mimicking naturalistic variability of healthy gait) patterning. The outcome measure for the walking task was change in the fractal scaling exponent (α) of step-time from uncued to cued walking. Contrary to our predictions, attentional load had no effect on change in the fractal scaling exponent (α). Regarding the auditory monitoring task, middle-aged and older adults, but not young adults, showed costs to task performance while walking as compared to while sitting. As predicted, fractal auditory cues improved long-range correlations in gait. This beneficial effect was qualitatively greater among middle-aged adults. Isochronous cues negatively affected long-range correlations in gait for middle-aged and older adults, but not younger adults. Contrary to our prediction, those with better beat perception were particularly disadvantaged when walking to isochronous auditory cues. Further, a lower fractal scaling exponent (α) at baseline was associated with a greater increase in the fractal scaling exponent (α) during cued walking.

Revisiting Gait Variability

A major theme of this program of research is the investigation of gait variability. Stride time variability is a sensitive marker of falls risk, even when no differences in mean gait parameters are observed (Hausdorff, 2005). Stride time variability as measured by the CoV of stride time reflects the overall magnitude of stride-to-stride fluctuations in gait. Conceptually, any deviation from the mean is considered error. However, Hausdorff (2009) points out that this is a simplified view of variability, and that some gait variability reflects the ability of the organism to adapt to changes in the environment. Indeed, among older adults with gait speed of ≥ 1.0 m/s, the association between gait variability and a history of falls was U-shaped, where older adults with the lowest and the highest step width variability were more likely to have fallen in the previous year (Brach et al., 2005). This suggests there is an optimal amount of gait variability, and that deviations from the optimal state have consequences for the health of older adults.

Fluctuations in stride time are not random but rather are characterized by long-range correlations, meaning that they have a predictable structure over time (Hausdorff et al., 1996). Non-random fluctuations have been observed across biological systems such as heart rate variability and are sometimes termed naturalistic variability. This naturalistic variability is thought to reflect the ability of biological systems to flexibly adapt to environmental changes (Stergiou & Decker, 2011). From this perspective, biological systems which are overly rigid and unchanging cannot adapt flexibly to a changing environment, and noisy and unstable systems are similarly disadvantaged. Optimal variability represents a state in which a biological system includes a range of movements and can flexibly adapt. The persistence of long-range correlations present in healthy gait breaks down with aging, as evidenced by lower fractal scaling exponents

(α) among older relative to younger adults (Kobsar et al., 2014a). There is evidence that this breakdown has health consequences for older adults. Among older adults with higher-level gait disorder the fractal scaling exponent (α), but not CoV, of stride time discriminated between those with and without a history of falls (Herman et al., 2005).

Theoretical Implications

This program of research was designed to better understand the attentional demands of RAS across the adult lifespan. We proposed that the dual-process model (Huxhold et al., 2006; Lövdén et al., 2008) would be useful in this respect. From a dual-process perspective, cued walking can benefit gait when the task conditions represent an optimal cognitive load. When the task demands are too low this can induce an internal focus of attention to the detriment of gait performance. When the task demands are too high, this results in cross-domain competition for attentional resources, also to the detriment of gait. Viewed through this framework, Papers 2 and 3 further nuance our understanding of the attentional demands of RAS and their impact on gait.

In Paper 2, middle-aged adults showed reduced gait variability while synchronizing their steps to tones in the *Simple* and *Moderate* conditions, relative to walking in silence. From a dual-process perspective, an optimal balance of external focus of attention and sufficient availability of cognitive resources was achieved in these conditions. During the *Complex* condition, however, the benefit to gait variability was attenuated suggesting that task demands exceeded resource capacity. The impact of RAS on gait was also related to individual differences in mobility in Paper 2. Older adults with better mobility were less likely to improve the consistency of their gait in the *Simple* condition. From a dual-process perspective, instructing older adults with better mobility to synchronize steps to tones may have resulted in an internal focus of attention to the detriment of gait, consistent with previous research with healthy older adults (Hamacher et al., 2016). In Paper 2, older adults wither poorer mobility were more likely to improve the consistency of gait in the *Simple* condition. Synchronizing steps to tones may have resulted in a "just right" attentional load for this subgroup thereby improving gait, as has been demonstrated in people with Parkinson's Disease (Cavanaugh et al., 2025). These findings suggest that benefiting from RAS to improve the consistency of gait is at least in part under cognitive control and relies on the availability of some attentional resources. Additionally, Paper 2 demonstrates the usefulness of the dual-process model to interpret deleterious and beneficial effects on gait during RAS.

Interestingly, in Paper 3 attentional load did not impact the change in fractal scaling exponent (α). A dual-task cost was observed in the concurrently performed auditory monitoring task, however, suggesting dual-task interference. Thus, both Papers 2 and 3 suggest that RAS is attentionally demanding, though this impact on gait was different. It is possible that modulating the long-range correlations of one's gait to match that of an external auditory pacing stimulus requires relatively fewer processing demands as compared to using an auditory pacing stimulus to reduce gait variability. This could explain why increasing attentional load negatively impacted step-time CoV (Paper 2) and not the long-range correlations in gait (Paper 3). If our cognitive task had been more difficult, we may have observed a disturbance in the long-range correlations of gait as well. This is in line with previous research showing a dual-task interference effect in the fractal scaling exponent (α) of stride time of older adults when concurrently performing a verbal fluency task, which draws on executive functioning (Lamoth et al., 2011). Taken together, our findings lend further support to the assertion that gait variability (e.g., step-time CoV) and naturalistic variability in gait (e.g., the fractal scaling exponent) are both potentially useful, but dissociable, aspects of gait.

More broadly speaking, discrepant findings from Papers 2 and 3 may point to a different balance of automatic and cognitive control processes in gait variability versus naturalistic variability in gait. In addition to being associated with motor-specific brain regions (e.g., primary sensorimotor cortex, supplementary motor cortex), increased gait variability among older adults has been associated with the anterior cingulate cortex, a brain region associated with higher-order cognition (Tian et al., 2017). Additionally, gait variability is correlated with measures of executive functioning (Hausdorff et al., 2005) and is sensitive to dual-task manipulation (Al-Yahya et al., 2011). These findings speak to a role of cognitive control, specifically attentional and executive control, in maintaining gait consistency. The origins of the fractal structure in stride-to-stride fluctuations in gait is less well-understood. Hausdorff and colleagues (1995) speculated that long-range correlations in gait may originate in central pattern generators thought to reside in the spinal cord and brain stem (Mason, 2017). More recent research has shown that long-range correlations in gait are disturbed in populations with neurodegeneration in the basal ganglia, suggesting a role for this structure in maintaining the temporal dynamics of healthy gait (Moon et al., 2016). Involvement of the spinal cord, brain stem, and basal ganglia speak to automatic control processes. Though, higher-order cognitive processes are also likely involved to some extent given the susceptibility of long-range correlations in gait to dual-task interference (Lamoth et al., 2011).

This collection of papers also contributes to the understanding of cognitive mechanisms underpinning facilitated gait during RAS. In Paper 2 we showed that selective auditory attention contributed to walking performance in the *Moderate* condition. In this condition, participants walked to tones of low and high pitch with the instruction to synchronize walking to the tones. Selective auditory attention may have supported individuals in extracting useful information (i.e., the beat) from the auditory scene to improve gait, while ignoring other less useful information (i.e., changes in pitch). Previous studies have shown that those with better beat perception show better walking performance when walking to rhythmic auditory cues (e.g., Cochen de Cock, 2018). However, we demonstrated that better beat perception is not always an advantage. In Paper 3 we found that, contrary to our prediction, those with better beat perception were disadvantaged in terms of the naturalistic variability of gait when walking to isochronous auditory cues. While immediately counterintuitive, this finding is in the end logical. Those with better beat perception were better able to adapt their gait to the auditory cueing stimulus. Adapting gait to isochronous cues resulted in gait which was less complex, like the stimulus itself. Better beat perceivers adapted particularly “well” to the isochronous stimulus, to the detriment of their naturalistic gait.

Middle-aged adults are underrepresented in lifespan studies of cognitive and motor aging (Lachman, 2015). This program of research addresses this gap by adopting a lifespan perspective and recruiting middle-aged adults aged 45-60 years old, as well as younger and older adults. Our research suggests that midlife may not simply exist “in between” young and older adulthood, but may represent a qualitatively different stage of the life course in certain respects. In Paper 2, the optimal attentional load for promoting consistent gait was different across age groups. Only the middle-aged adults showed the expected improvement in the *Simple* condition and attenuation in the *Complex* condition. As described above, these results are in line with the dual-process model and demonstrate that the task conditions which characterize the “optimal” cognitive load depends in part on age group. In Paper 3 middle-aged adults benefitted more from the auditory pacing stimulus to improve the naturalistic variability in their gait relative to other age groups. This appeared to be related to a lower fractal scaling exponent (α) among middle-aged adults at baseline relative to other age groups. Given the dearth of studies investigating naturalistic variability in gait among middle-aged adults it is not known whether middle-aged adults have lower naturalistic variability generally or whether this was specific to our sample. Previous studies have reported that middle-aged adults have a fractal scaling exponent (α) of 0.80 (Terrier & Dériaz, 2012) and 0.73 (Homs et al., 2022) at preferred walking speed. However, these studies measured treadmill walking and their samples were significantly younger than ours, which may explain differences in estimates. These findings speak to the need of obtaining larger samples of middle-aged adults to better characterize gait across the adult lifespan. Larger samples would also permit sex-based analyses which are critical to understanding sex/gender disparities in health generally (Eliot et al., 2023), and particularly among middle-aged adults given hormonal shifts experienced by women in midlife (Schwartz & Villa, 2024).

Clinical Implications: Optimizing Rhythmic Auditory Stimulation

The findings from this research program have implications for clinical decision-making. Specifically, I will discuss the implication of our results for decisions regarding task complexity, the temporal structure of cues, and task instruction during RAS for gait rehabilitation.

Researchers have previously suggested that synchronizing steps to tones during RAS is cognitively demanding (Leow et al., 2018), and findings from Papers 2 and 3 provide empirical support for this assertion. In Paper 2 the consistency of gait of middle-aged adults was negatively impacted in the most complex task conditions. Beneficial effects were observed in the simplest task conditions for middle-aged and a subgroup of older adults. These findings have at least three clinical implications. Firstly, candidates for gait rehabilitation interventions will likely have lower motor functioning, and possibly lower cognitive functioning, compared to the healthy middle-aged adults in our sample. As such, they may be vulnerable to complexity effects at lower levels of attentional load. It may therefore be helpful to reduce the attentional load of RAS as much as possible, for example by limiting distraction. Secondly, we structured the Listening task such that as task complexity increased, the Listening task became less integrated with the motor task. Integrated in this case meaning being relevant to the rhythmic features of the auditory stimulus. Our results suggests that RAS interventions which are more integrated into the motor task are more likely to benefit to gait, analogous to the *Simple* condition in our study. For example, if the music is specifically designed to enhance beat salience, as in high-groove music (Leow et al., 2021), then this may direct the person's attention towards the beneficial (rhythmic) aspects of the stimulus. Thirdly, clinicians may aim to integrate patient preferences to increase motivation and treatment adherence. Our results suggest that these should be balanced with the cognitive demands of the intervention. Consistent with this view, individuals have reported that it would be more enjoyable to walk to music, and at the same time have reported that synchronizing to music was more difficult than synchronizing to a metronome (Marmelat et al., 2020). In this case positive effects were observed for metronome cueing but not music cueing. Clinicians may find it helpful to consider attentional load, how different elements of music are integrated (or not) with the clinical goal of the intervention, as well as patient preferences.

Previous research with people with Parkinson's Disease has found that auditory cues with fluctuations which mimic the naturalistic (i.e., fractal-like) variability of healthy gait improve long-range correlations in gait (Marmelat et al., 2020), whereas isochronous auditory cues result in a more random gait pattern (Dotov et al., 2017). In Paper 3 we extended these findings by demonstrating these effects among healthy individuals across the adult lifespan. From a clinical perspective, if the target outcome of rehabilitation is to improve the long-range correlations in gait, then embedding the auditory stimulus with a fractal rhythm would be advised. However, if the target outcome is to improve gait consistency, then isochronous cues could be used. However, one should be mindful that the benefit of isochronous cues to gait consistency may come at a cost to the naturalistic variability in gait, particularly for those with better beat perception as demonstrated in Paper 3. There is still much to learn regarding the functional significance of increases and decreases in long-range correlations in gait (see discussion for future directions below). However, gait which exhibits fractal patterning is thought to be more adaptable and better suited to adjust to environmental changes (Stergiou et al., 2016). This has been demonstrated experimentally, where young adults with fractal scaling exponents closer to $\alpha = 1.0$ during asymmetric walking showed better gait adaptability (Ducharme et al., 2018). Those who deviated from $\alpha = 1.0$, either higher or lower, showed poorer adaptation to asymmetric walking. Further, older adults with a history of falls show a breakdown of the fractal patterning of gait, exhibiting more random stride-to-stride fluctuations (Herman et al., 2005). Restoring fractal patterns in gait may be a useful clinical goal to improve gait adaptation and reduce risk for falls.

Previous studies have shown mixed results regarding instructing individuals to synchronize their steps to tones with some showing a beneficial effect (Ready et al., 2022) and others showing a detrimental effect (Leow et al., 2018). In the current research program, all participants were instructed to synchronize their steps to tones. In Paper 2 there was a wide range of effects among older adults, with some older adults improving their gait consistency and others showing less consistent gait during cued walking relative to walking in silence. As discussed above, follow-up analyses showed that older adults with poorer baseline mobility improved their gait consistency under simple task conditions, whereas older adults with better baseline mobility were more likely to show deleterious effects. This suggests that individuals with poorer mobility and motor performance at baseline, as would likely be the case for candidates for gait rehabilitation, may benefit from instructions to synchronize their steps to tones.

Limitations

In the current program of research all 3 papers are derived from a single dataset. This allowed us to integrate several research questions into one overarching research design, which was economical from a financial and resource perspective. The current dataset is quite rich, involving no less than two measurement devices, three conditions of complexity, auditory cues with two different temporal structures, and three age groups. We were therefore able to make several comparisons which may not have been practical if each research question had been planned in a separate sample. However, the drawbacks of this strategy are that limitations that occur in one paper tended to repeat themselves across papers, and that we could not run a replication study.

Sample characteristics limit the generalizability of Papers 1, 2, and 3. In particular, the older adults recruited for our study were high functioning, as evidenced by the few differences in cognitive and motor performance relative to middle-aged and younger adults. Older adults were recruited from pre-existing contact lists and from a community gym, which likely influenced sample characteristics. This limits the generalizability of our results to patient populations who are more likely to have cognitive and motor deficits. A related limitation is the imbalance of genders across groups, such that more women participated in the study than men. Analyses investigating sex-related differences are increasingly common in cognitive-neurosciences, with important differences being found (Dotson & Duarte, 2020). Women undergo important hormonal shifts in midlife which spur cognitive and physiological symptoms (Metcalf et al., 2023). While sex-based effects were not supported in the current collection of papers, the distribution of genders across groups may have occluded any effects.

The limited number of steps used to quantify gait is a limitation of papers 1 and 3. Walking trials were approximately two minutes in duration to minimize participant burden given the number of experimental conditions completed. As it was, participants completed the experimental conditions in a single session lasting 2 – 2.5 hours. The relatively low number of steps per trial in Paper 1 limited our ability to accurately estimate the reliability and validity of the Noraxon FootSwitch system to measure gait variability. For Paper 3, our estimation of the fractal scaling exponent (α) was also limited by the number of steps captured. Some researchers estimate that 500-600 observations are required to accurately estimate α (Damouras et al., 2010; Marmelat & Meidinger, 2019). However, as few as 100-200 may be adequate when focusing on group comparisons (Phinyomark et al., 2020). Following this guideline, we placed greater emphasis on the direction of change of fractal scaling exponent (α) with experimental manipulations and groups differences rather than seeking to describe precise estimates for each age-group. Estimates from Paper 3, particularly for middle-aged adults who are less well represented in the literature, should therefore be interpreted with caution and should be replicated in future studies.

Another limitation of the current research program is the missing data on the auditory monitoring task which appears in Papers 2 and 3. The missing data were due to equipment failure which occurred at a time in our recruitment schedule when the young adult sample was nearly complete. We were in the early stages of data collection when the COVID-19 pandemic occurred. We paused data collection for approximately one year. When we started recruiting again, for safety we recruited young adults first. As the COVID-19 vaccines became more widely available and standard operating procedures were in place to reduce the risk of transmission of COVID-19, we recruited middle-aged and then later older adults to participate. The equipment failure occurred in the later stages of our data collection, and therefore middle-aged and older adults were more affected. Given the nature of the data loss, we determined that the data were missing completely at random and not likely a source of systematic bias. Nevertheless, the missing data likely resulted in low power and increased likelihood of Type II statistical error. This conclusion is supported by the discrepant results obtained in Papers 2 and 3. In Paper 2 only the isochronous conditions were used, and no dual-task effects were observed. In Paper 3, isochronous and fractal auditory conditions were included in the analyses, and dual-task effects were observed for middle-aged and older adults. The increase in power achieved by including both the fractal and isochronous conditions likely explains the detection of a dual-task effect in Paper 3 which was not detected in Paper 2. Cue type did not statistically significantly contribute to model fit regarding performance on the auditory monitoring task, supporting the validity of interpreting performance across isochronous and fractal trials.

Another limitation of the auditory monitoring task was that because some participants scored 0 during single-task conditions, a DTC score would be undefined due to the presence of 0 in the denominator of the calculation. Hits minus false alarms was used instead. We could therefore not compare *change* in performance in the Walking task with *change* in performance in the Listening task, which would be a better indicator of possible trade-offs during dual tasking. This limited our ability to comment on task prioritization during RAS.

Future Directions

Despite the limitations described above regarding the auditory monitoring task, the Listening task had several strengths. For example, the construction of our Listening task allowed us to orthogonally manipulate task complexity and the temporal structure of the auditory cues, and to investigate these dimensions independently within the same research design. Further, different elements of music may present different cognitive loads or recruit different cognitive abilities. Our Listening task allowed us to isolate changes in pitch, as in the *Moderate* condition, and we found that selective auditory attention specifically supported a positive response to RAS given this musical element. Changes in pitch are, of course, common in music and therefore our chosen task increased the ecological validity of our investigations. To complement our research, future studies could use more traditional cognitive tasks (e.g., n-back, serial subtractions) to investigate cognitive-motor trade-offs in the context of RAS. Finally, we constructed the Listening task such that it was not fully integrated into the motor task, but not fully separate either. As the Listening task became more complex, it moved towards being less integrated into the motor task. We concluded that the more integrated the motor task, the more likely there will be a benefit to gait. This opens interesting avenues for future research, such as whether dance, in which the cognitive and motor tasks are fully integrated, could be integrated into gait rehabilitation.

Researchers could also broaden their investigation of task instructions during RAS. Instructions during RAS are typically limited to the instruction to synchronize one’s steps to the beat, or to walk freely. Efforts to determine which instruction yields the most benefit have been mixed, with some studies showing a benefit when participants are instructed to synchronize (Ready et al., 2022), and some studies showing a cost (Leow et al., 2018). At the same time, synchronizing steps to tones may be an important to maximize the benefit of RAS (Cochen De Cock et al., 2018). Our results suggest that among older adults with better motor functioning, the instruction to synchronize steps to tones may lead to an internal focus of attention thereby disrupting automatic processes in gait control. Other forms of instruction that promote synchronization while considering attentional focus (i.e., without inducing an internal focus of attention) are an avenue for future research. For example, different sets of instructions like "use the music to help you walk" versus "walk to the beat of the music" versus "take big steps to the music" and their impact on gait and synchronization performance could be investigated in future studies.

In Paper 2 we showed that walking to simple auditory cues improved the gait consistency of a subset of older adults. While not reported in the main text, we conducted further analyses which indicated that older adults who did not benefit in the *Simple* condition continued to not benefit in the *Moderate* and *Complex* conditions. Similarly, those who benefitted did so in all conditions. We did not observe differences between subgroups on performance of the auditory monitoring task. However, our ability to draw firm conclusions about these subgroups is limited by the small sample size of subgroups as well the limitations of the auditory monitoring task, discussed above. We might hypothesize that subgroups of older adults may have used different strategies to navigate dual-task conditions which we were unable to detect. For example, older adults who benefited may have adopted a "posture first" strategy. Future studies can over recruit older adults so that subgroup analyses regarding potential trade-offs between cognitive and motor performance can be performed.

In Paper 3, we suggest that benefits to spatiotemporal parameters of gait such as gait speed and stride length during cued walking to isochronous cues may come at a cost to the long-range correlations typically present in healthy gait. While long-range correlations in gait are characteristic of a healthy system, the functional significance of a breakdown of this temporal structure in gait requires further research. Longitudinal studies investigating the temporal dynamics in gait and how these are associated with health outcomes are needed. Future studies can also investigate musically cued gait training with two groups: in one group music during RAS would be embedded with isochronous cues and in the other music would be embedded with fractal cues. Ideally, spatiotemporal parameters as well as temporal dynamics of gait would be measured pre- and post-training to determine the impact of each cue type on the various parameters of gait. Follow up investigations post-training should also evaluate if groups differ in terms of falls risk. This would further clarify the functional implications of using fractal versus isochronous cues for gait rehabilitation.

Conclusions

Stable and consistent gait is central to the safety and autonomy of older adults. RAS is an evidence-based intervention for the rehabilitation of gait which can improve spatiotemporal gait parameters among older adults. While there is a growing body of research suggesting that synchronizing steps to tones is cognitively demanding, our understanding of how attentional load impacts gait during RAS is limited. The current program of research further clarified the attentional demands of RAS and the impact on gait variability by investigating cognitive-motor interactions in this context using a dual-task design. We have provided empirical support for the applicability of the dual-process model in conceptualizing beneficial versus deleterious effects on gait during RAS. Further, we have elucidated how individual differences in cognitive, motor, and perceptual rhythmic abilities moderate response to RAS across the adult lifespan. I hope that the findings outlined in this dissertation will contribute to the investigation of cognitive-motor interactions in the context of RAS with the overarching goal of informing clinical gait rehabilitation programs and improving quality of life for older adults.

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