Motor and cognitive deficits limit the ability to flexibly modulate spatiotemporal gait features in older adults with mild cognitive impairment

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Abstract

Dance-based therapies are an emerging form of movement therapy aiming to improve motor and cognitive function in older adults with mild cognitive impairments (MCIs). Despite promising effects of dance-based therapy on function, it remains unclear how age-related declines in motor and cognitive function influence which movements and rhythms maximize dance therapy efficacy. Here, we evaluated the effects of age and MCI on the ability to accurately modulate spatial (i.e., joint kinematics), temporal (i.e., step timing), and spatiotemporal features of gait to achieve spatial and temporal targets during walking. We developed novel rhythmic movement sequences - nine spatial, nine temporal, and four spatiotemporal - that deviated from typical spatial and temporal features of walking. Healthy young adults (HYA), healthy older adults (HOA), and adults with MCI were trained on each gait modification before performing the modification overground, with kinematic data recorded using wearable sensors. HOA performed spatial ($p = 0.010$) and spatiotemporal ($p = 0.048$) gait modifications less accurately than HYA. Individuals with MCI performed spatiotemporal gait modifications less accurately than HOA ($p = 0.017$). Spatial modifications to the swing phase of gait ($p = 0.006$, Cohen's $d = -1.3$), and two- and four-step *Duple* rhythms during temporal modifications ($p \leq 0.030$, Cohen's $d \geq 0.9$) elicited the largest differences in gait performance in HYA vs. HOA and HOA vs. MCI, respectively. These findings suggest that age-related declines in strength and balance reduce the ability to accurately modulate spatial gait features, while declines in working memory in individuals with MCI may reduce the ability to perform longer temporal gait

modification sequences. Differences in performance on rhythmic movement sequences highlight the impacts of motor and cognitive deficits on gait modulation capacity, which may assist therapists in personalizing therapies based on these deficits and provide more sensitive indices to track intervention efficacy.

1 Introduction

Dance-based therapy is an emerging form of movement therapy for individuals with mild cognitive impairments (MCIs), a precursor to dementia or Alzheimer's involving reduced attention, executive function, spatial cognition, and working memory that elicit improvements in cognitive function in individuals with MCI (Gauthier et al., 2006; Lazarou et al., 2017; Sanford, 2017; Zhu et al., 2018; Zhu et al., 2020). Dance-based therapy is a logical approach for improving cognitive function, as exercise or general physical activity are among the few interventions shown to improve cognitive function in individuals with MCI (Geda et al., 2010; Thom and Clare, 2011). Specifically, Thom and Clare (2011) noted that physical exercise programs that target functional tasks, aerobic endurance, and balance are likely needed to maximize the functional benefits of therapy, all of which are challenged during dance (Thom and Clare, 2011). Currently, it is unclear how to personalize dance-based therapy parameters in MCI. Studies of dance-based therapy use different music, dance types, and study designs (Hackney and Earhart, 2009; McKee and Hackney, 2013; Lazarou et al., 2017; Zhu et al., 2020). Improving our understanding of the relationships between individuals' motor and cognitive function and dance-based therapy performance is necessary to guide optimal selection of music and dance movements for individuals with MCI.

While a major goal of dance-based therapies is to maximize the motor and cognitive benefits of moving to music, *how* to do so for a given population needs better clarity. Music type and tempo, and the dance type or steps are basic parameters that can influence the difficulty of performing the therapy routine. Many therapies rely on trial-and-error to finetune a protocol, rather than being grounded in a principled understanding of how individuals' diverse motor and cognitive function levels influence responses to therapy (McKee and Hackney, 2013; Lazarou et al., 2017; Zhu et al., 2018). Selecting an appropriate level of challenge is foundational to maximizing the motor and cognitive effects of therapy (Guadagnoli and Lee, 2004). Given the heterogeneity of deficits in MCI (Gauthier et al., 2006), understanding how both motor and cognitive deficits impact the ability to perform challenging rhythmic movement patterns may both enable objective personalization of dance-based therapy parameters and provide mechanistic insights into the impacts of MCI on mobility.

Though not yet quantified in the context of dance-based therapy, dance can be considered a series of Rhythmic Movement Sequences (RMS) – rhythmic patterns involving modifications to spatial and temporal components of normal stepping (Rallis et al., 2018). Importantly, spatial and temporal features of movement correspond to distinct neural representations (*e.g.*, the premotor cortex) and multiple biomechanical mechanisms (*e.g.*, strength, balance, joint coordination) (Wilson and Kwon, 2008; Kornysheva and Diedrichsen, 2014). In this work, we focus on the spatial and temporal components of lower limb movements during gait. Spatial modifications of movement during dance involve altering the magnitude and coordination of hip, knee, and ankle kinematics (Ivanenko et al., 2005; Wilson and Kwon, 2008). Voluntarily altering coordination relative to highly stereotyped coordination patterns during locomotion requires the motor capacity to achieve joint excursions and increased cortical demands (Ivanenko et al., 2005; Cohen et al., 2016; Hortobágyi et al., 2016; Rucco et al., 2017). Ballet movements exemplify the potential motor and cognitive challenges of modifying gait. For example, during the ballet movement *battement*, hip flexion is accompanied by knee extension and ankle plantarflexion when swinging the leg forward. Additionally, peak joint excursion timing may be altered relative to normal walking, such as achieving maximal ankle plantarflexion during mid-stance in the *piqué* movement. While motor and cognitive deficits are known to induce subtle changes in joint kinematics, it remains unclear how these deficits impact the ability to voluntarily modulate gait kinematics (Rucco et al., 2017).

Analogously, temporal gait modifications during dance involve altering step timing to produce rhythmic sequences of steps. Temporal modifications can be elicited by cueing rhythm and meter, two fundamental components of music that often accompany dance and RMS. In the context of stepping or walking, rhythm describes patterns of steps of a specific duration, such as two quick (*q*) steps followed by two slow (*S*) steps. Meter is a perceived quantity encoding an individual's anticipation of beats, inferred from repetitions of the temporal rhythm (London, 2012). For example, common meters in Western music include duple (two-count) and triple (three-count). Rhythm defines the structure of temporal stimulus, while behavior is entrained to the meter of music or temporal cues, possibly eliciting neurophysiological responses (Lerdahl and Jackendoff, 1983). For unimpaired adults, walking involves a simple rhythm with evenly recurring steps that are approximately rhythmically and metrically constant, such that temporal gait modifications represent a deviation from normal gait rhythms.

A central premise of this work is that evaluating the capacity for modulating spatial and temporal movement features will shed light on motor and cognitive mechanisms that may inform individualization and enhance the efficacy of dance therapy in individuals with MCI. RMS challenge motor function in the form of balance and strength requirements for performing spatial and spatiotemporal modifications. Additionally, deviations from normal magnitude and timing of movement patterns make RMS a form of dual-tasking, challenging cognitive function: individuals must listen to and process instructional and musical cues to which they coordinate spatial and temporal movement patterns during gait. Because RMS require attention and the ability to map perceived biomechanical targets and rhythmic cues to motor actions, we expect it to challenge multiple aspects of cognitive function that are reduced in individuals with MCI: s*patial* a*ttention, executive function*, s*patial cognition*, and *working memory* (Gauthier et al., 2006). Consequently, spatial modification structure and temporal complexity are likely to impact modification performance in individuals with MCI. Further, isolating spatial and temporal RMS features may highlight distinct motor and cognitive mechanisms contributing to reduced RMS performance, potentially informing dance therapy personalization.

In this study, we leveraged biomechanical analysis, prototypical dance movements, and music theory to systematically investigate the effects of motor and cognitive function on the ability to perform spatial and temporal gait modifications in individuals with MCI. We hypothesized that age and cognitive function would impact the abilities of healthy young adults (HYA), healthy older adults (HOA), and adults with MCI to achieve biomechanical and temporal targets when performing spatial, temporal, and spatiotemporal gait modifications of varying difficulty. We hypothesized that differences in motor and cognitive function between HYA, HOA, and MCI would impact individuals' abilities to achieve spatial and temporal targets during RMS. Specifically, we predicted that HOA would perform RMS significantly less accurately than HYA (motor effects) and that individuals with MCI would perform RMS less accurately than HOA (cognitive effects).

2 Materials and Methods

This study was approved by the Emory University Institutional Review Board (STUDY00003507). All participants gave written informed consent prior to participation.

2.1 Study design and visits

We performed an observational cross-sectional study in healthy younger and older adults, and in older adults with MCI. All outcomes were collected during a single 2-4 hour study visit for each

participant. Participants who were unable to complete the protocol in a single visit (N=1) completed it during one additional visit within one week.

2.2 Participants

Participants included younger adults (HYA, N=12), older adults (HOA, N=12), and older adults with MCI (N=12). Clinical and demographic characteristics are shown in **Table 1**. For all participants, inclusion criteria included the ability to walk 20m without an assistive device, completion of at least 6 years of education or good work history, no hospitalizations in the last 60 days, and proficiency in the English language. Additional inclusion criteria for participants with MCI included amnestic MCI defined using the Alzheimer's Disease Neuroimaging Initiative criteria and reduced executive function, working memory, and spatial cognition according to standard clinical assessments (Phillips et al., 2001; Vandierendonck et al., 2004; Mueller et al., 2005; Bowie and Harvey, 2006; Hackney et al., 2013).

Table 1: Demographic characteristics of each participant group.

	HYA	HOA	MCI	Total	p-value
N	12	12	12		
Age					< 0.01
Mean (SD)	23.9 (4.2)	67.3 (10.5)	69.5 (7.0)	53.6 (22.6)	
Range	18.0 - 30.0	53.0 - 80.0	57.0 - 79.0	18.0 - 80.0	
Height					0.73
Mean (SD)	65.1 (3.7)	66.3 (3.6)	65.6 (3.9)	65.7 (3.6)	
Range	62.0 - 75.0	62.0 - 72.0	60.0 - 72.0	60.0 - 75.0	
Weight					0.08
Mean (SD)	137.8 (28.1)	158.6 (32.6)	165.4 (28.4)	153.9 (31.3)	
Range	110.0 - 200.0	114.0 - 210.0	128.0 - 240.0	110.0 - 240.0	
Sex					0.69
F	9 (75%)	8 (67%)	7 (58%)	24 (67%)	
M	3 (25%)	4 (33%)	5 (42%)	12 (33%)	
Years since MCI	-	-	3.2 (2.2)	-	-

2.3 Motor and cognitive assessments

To characterize participants' motor and cognitive function, trained personnel administered the following motor and cognitive assessments: Montreal Cognitive Assessment (MoCA), Reverse Corsi Blocks test, Tower of London test, Trail Making Test, Four-Square Step Test, Body Position Spatial Task, simple, manual, and cognitive Timed Up-and-Go (TUG), and the 30-second Chair Stand (Lundin-Olsson et al., 1998; Jones et al., 1999; Morris et al., 2001; Phillips et al., 2001; Dite and Temple, 2002; Vandierendonck et al., 2004; Nasreddine et al., 2005; Bowie and Harvey, 2006; Hackney et al., 2013). The average (± 1SD) for each clinical assessment and p-values denoting the probability of statistical differences in each score were computed using the software package R (

Table 2). Older adults and individuals with MCI were well matched in age and sex. As expected, the MCI participants performed worse on the tests of motor and cognitive function. HYA participants performed better than HOA or MCI participants on all assessments of motor and cognitive function.

Table 2: Clinical characteristics of each participant group.

	HYA	HOA	MCI	Total	p-value
N	12	12	12		
Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005)					0.02
Mean (SD)	28.4 (2.2)	27.8 (2.1)	25.7 (2.6)	27.5 (2.4)	
Range	22.0 - 30.0	24.0 - 30.0	22.0 - 29.0	22.0 - 30.0	
*N-Miss**	0	0	1	1	
Trail Making Test (B-A) (Bowie and Harvey, 2006)					0.1
Mean (SD)	24.3 (13.9)	22.3 (23.2)	42.1 (29.0)	29.0 (23.4)	
Range	7.9 - 50.4	-95.8	-101	-109.9	
N-Miss	0	1	2	3	
Tower of London (Phillips et al., 2001)					0.06
Mean (SD)	20.2 (5.2)	17.3 (2.4)	15.8 (5.0)	17.8 (4.7)	
Range	14.0 - 29.0	13.0 - 21.0	6.0 - 25.0	6.0 - 29.0	
Reverse Corsi Blocks (Vandierendonck et al., 2004)					< 0.01
Mean (SD)	59.6 (21.2)	31.8 (16.4)	24.0 (15.4)	38.5 (23.2)	
Range	15.0 - 98.0	0.0 - 60.0	0.0 - 54.0	0.0 - 98.0	
Four-Square Step Test (Dite and Temple, 2002)					< 0.01
Mean (SD)	7.3 (1.5)	9.6 (1.5)	10.8 (2.1)	9.3 (2.2)	
Range	5.9 - 10.9	7.6 - 13.1	8.0 - 15.4	5.9 - 15.4	
N-Miss	1	0	0	1	
Body Position Spatial Task (Hackney et al., 2013)					< 0.01
Mean (SD)	31.2 (15.5)	17.0 (10.0)	11.3 (8.6)	19.8 (14.2)	
Range	12.0 - 70.0	0.0 - 35.0	0.0 - 25.0	0.0 - 70.0	
Timed Up-and-Go (TUG) (Morris et al., 2001)					0.36
Mean (SD)	6.2 (0.9)	6.7 (2.4)	7.7 (3.7)	6.9 (2.6)	
Range	4.6 - 7.6	0.0 - 9.2	0.0 - 14.9	0.0 - 14.9	
Manual Timed Up-and-Go (Lundin-Olsson et al., 1998)					0.01
Mean (SD)	8.3 (0.6)	8.8 (1.5)	11.1 (3.6)	9.3 (2.5)	
Range	7.3 - 9.6	6.8 - 11.5	7.9 - 18.8	6.8 - 18.8	
N-Miss	0	1	1	2	
Cognitive Timed Up-and-Go (Morris et al., 2001)					0.02
Mean (SD)	9.3 (4.7)	11.4 (3.2)	15.2 (6.3)	11.9 (5.3)	
Range	6.1 - 23.4	7.2 - 19.6	8.9 - 28.4	6.1 - 28.4	
N-Miss	0	1	1	2	
30-second Chair Stand (Jones et al., 1999)					0.09
Mean (SD)	16.2 (3.0)	13.9 (3.4)	12.8 (4.6)	14.3 (3.9)	
Range	10.0 - 21.0	9.0 - 22.0	4.0 - 23.0	4.0 - 23.0	

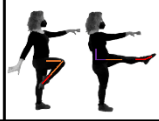
2.4 RMS gait modifications

Participants performed normal walking at their self-selected and fast speeds, and 22 RMS consisting of 9 spatial, 9 temporal, and 4 spatiotemporal gait modifications, described below. Participants were randomly assigned to perform either the spatial or temporal modifications first. Spatiotemporal

modifications always occurred after spatial and temporal modification trials. Experimental conditions within each sub-group (spatial, temporal, or spatiotemporal) were randomized.

We defined 64 spatial, temporal, and spatiotemporal gait modifications, constituting a movement library, from which we selected 9 spatial, 9 temporal, and 4 spatiotemporal gait modifications of varying levels of difficulty. The selected biomechanical (*i.e.*, spatial) and temporal features of each modification are described in **Figure 1**. Briefly, *spatial* modifications altered the magnitude of hip, knee, and ankle movements and their coordination relative to normal walking (Ivanenko et al., 2005). We selected three stance-phase modifications (ST), three swing-phase modifications (SW), and three combined modifications in both the swing and stance phases (SWST). Participants were provided target joint angles for each modification, such as flexing the hip and knee to 90 degrees during swing; and watched a video of an expert dancer performing the movements. During ST and SW trials, participants modified stance and swing-phase gait kinematics, respectively, in both legs asymmetrically. During SWST trials, participants modified both swing and stance only in the left leg.

A) *Spatial gait modifications*

Swing		Stance	
Biomechanical Target	Gait modification	Biomechanical Target	Gait modification
▪ 45° knee flexion ▪ Max. ankle plantarflexion ▪ Toe at stance - leg ankle	Coupé	▪ 0° knee flexion ▪ Max. ankle plantarflexion throughout stance	Piqué
▪ 90° knee flexion ▪ Max. knee flexion ▪ Toe at stance - leg knee	Passé	▪ 30° knee flexion ▪ 30° ankle dorsiflexion	Tombé
▪ 90° hip flexion ▪ 90° knee flexion ▪ Max. ankle plantarflexion	Attitude	▪ 0° knee flexion ▪ Max. ankle dorsiflexion	Heel strike
▪ 90° hip flexion ▪ Max. early - swing knee flexion ▪ 0° late-swing knee flexion ▪ Max. ankle plantarflexion	Developpé 	▪ 0° knee flexion ▪ Max. ankle plantarflexion in mid-stance	Relevé
▪ 90° hip flexion ▪ 0° knee flexion ▪ Max. ankle plantarflexion	Battement		

B) *Attitude*

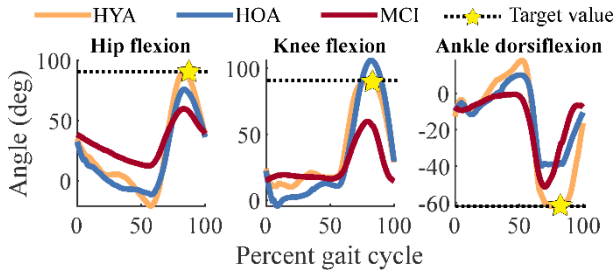


Figure 1: Descriptions of subcomponents of the spatial modifications. A) Spatial gait modifications were derived from ballet steps, noted in the boxes containing movement depictions. The left two columns correspond to swing-phase modifications, while the right two columns correspond to stance-phase modifications. Each depiction shows the modification where biomechanical targets were applied. Colored lines on each person denote biomechanical targets at the hip (purple), knee (orange), and ankle (red) kinematics that were used to evaluate movement performance. Bulleted lists describe the biomechanical targets for each

gait modification, which were used to quantify movement performance. Bulleted lists denote the biomechanical targets for each gait modification. Modifications were performed in pairs during spatial trials. B) Example of biomechanical targets for the *Attitude* gait modification. Black dashed lines denote biomechanical target values and gold stars denote where the target value was estimated. For example, during the *Attitude* modification, the swing-leg hip (left) and knee (middle) should be flexed to 90 degrees, and the ankle (right) should be maximally plantarflexed. Colored lines denote exemplary HYA (orange), HOA (blue), and MCI (red) participants. These participants highlight reduced RMS performance at the hip and knee in MCI and at the ankle in HOA and MCI.

Temporal modifications altered the rhythmic patterns of movement, consisting of four or six steps taken at one-beat ("quick;" *q*), two beats ("slow;" *S*), and half-beat ("and;" &) durations (**Figure 2**). Modifications were split into three sub-groups: three simple duple, three complex duple, and three waltz modifications in compound duple or simple triple meter. *Duple* music had a tempo of 100 beats per minute (bpm) for all participants, while Waltz music had a tempo of 134 bpm for HYA but was reduced to 104 bpm for the HOA and MCI groups due to difficulties matching the faster tempo. The *simple duple* meter has a two-count grouping (1-2) where the downbeat is the strong beat. In more *complex duple* meters that feature syncopations, the emphasized beat falls on the weak beat, which defies Western music listeners' expectations. Consequently, we expected the complex duple to be more challenging than the simple duple. The waltz is in a compound duple meter (a fast two-count where each is subdivided into three sub-beats) or simple triple (three-count) meter. Unlike *simple* and *complex duple* meters, in which synchronization of movement to music is easier because the same foot always lands on the downbeat, the three-count of *waltz* rhythms causes the foot landing on the downbeat to alternate every measure (three steps). Consequently, individuals accustomed to Western music traditions may have greater difficulty synchronizing movements to the triple meter of *waltz* than to duple meters. The movements within each sub-group varied in difficulty. During duple trials, participants were cued by a simplified *Libertango* (Astor Piazzolla, 1974), with superfluous accents and musical cues eliminated to simplify the rhythmic grouping and metrical structure. We expected the less-complex rhythm to improve the ability of participants with limited musical experience to identify temporal patterns in the music. During waltz trials, participants were cued by a modified version of *Shostakovich Waltz No. 2* (Dmitri Shostakovich, 1938). These musical pieces are much more complex than a metronome beat used in locomotion studies, as the attention required to dissociate meter and rhythm from superfluous auditory information can alter individuals' abilities to entrain to the tempo (Styns et al., 2007; Moumdjian et al., 2019). For each modification, participants were provided a sequence of "quick" and "slow" beats and practiced the sequence by following an instructional video: first clapping, then tapping the foot, then shifting weight between the legs, then stepping in place, then walking (Hackney and Earhart, 2010).

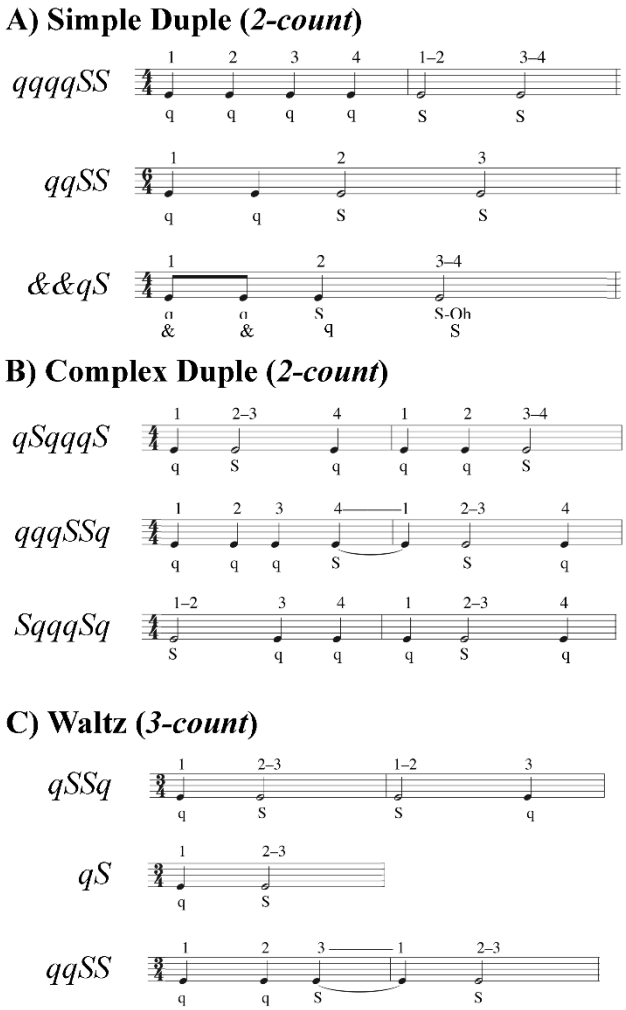


Figure 2: Step sequences for temporal and spatiotemporal gait modifications. Step sequences consisted of 2, 4, or 6 steps. Each sequence specified a combination of very quick (& = half-beat), quick (*q* = one beat), and slow (*S* = two beats) steps. The numbers above the musical bars show the beat count for each rhythm. A) Simple duple sequences used a two-count rhythm in which the strong beat was the downbeat. B) Complex duple sequences also used a two-count rhythm, but the strong beat was not the downbeat. C) Waltz sequences used a three-count rhythm, such that sequences spanned either one or two measures.

Spatiotemporal modifications combined spatial and temporal modifications. Specifically, we selected combinations of easy spatial and hard temporal modifications, hard spatial and easy temporal modifications, easy spatial and temporal modifications, and hard spatial and temporal modifications (**Figure 1** & **Figure 2**). We selected these movements to vary the relative motor and cognitive challenges of the movements. Participants were allowed to review spatial and temporal instructional videos if needed. Following instructions for all modifications, the assessors would briefly practice (3-

5 sequences) the modifications with the participant to confirm understanding. Data were collected immediately after understanding was confirmed.

During each trial, participants wore 15 inertial measurement units (IMUs) in a standard configuration (APDM, Inc., Portland, USA). We used validated commercial software associated with the IMUs to estimate lower-limb hip, knee, and ankle flexion angles over the gait cycle (Mancini and Horak, 2016; Washabaugh et al., 2017). Participants began each trial in quiet stance until hearing a tone, then began walking in a modified gait pattern defined by the trial's spatial, temporal, or spatiotemporal RMS. When physically capable, participants walked overground along an 11m walkway four times for each trial, providing 15-30 (spatial) or 15-60 (temporal) strides for each trial. For participants with reduced physical capacity, we iteratively reduced the number of walkway lengths traveled from four lengths down to one length based on each participant's physical capacity. We ensured that each participant performed at least 15 strides for spatial modifications and 10 sequences for temporal and spatiotemporal modifications. Participants were allowed to rest as needed and were provided snacks and water between trials. All assessments were administered by trained personnel.

2.5 RMS performance

For each modification, we defined biomechanical (spatial and spatiotemporal trials) and temporal (temporal and spatiotemporal trials) targets, defined *a priori* in our movement library (**Figure 1**). Biomechanical targets matched those provided during instruction. Temporal targets corresponded to the step sequence of quick and slow steps. RMS performance was defined as a percent error relative to biomechanical and temporal targets: the error relative to each target value, normalized by the magnitude of the corresponding target. Therefore, RMS performance reflected the accuracy with which each participant performed a gait modification, with lower percent error reflecting more accurate (*i.e.*, better) performance. For each trial and participant, we averaged across the trial's biomechanical and temporal targets.

2.5.1 Statistical analysis

We examined differences in RMS performance across groups using separate fixed effects linear models for each outcome variable. To test for group differences in RMS performance between the HYA and HOA groups, and between HOA and MCI groups, we used linear models containing indicator variables denoting the HYA and MCI groups, with HOA as the reference group (Equation (1). Significant coefficients (Wald Tests, $\alpha = 0.05$) corresponding to the HYA (β_{HYA}) or MCI variables (β_{MCI}) would indicate significant differences in performance between the HOA group and the HYA or MCI groups, respectively. Separate linear models were fit for each gait modification class (*spatial, temporal, spatiotemporal*). To determine which movements best distinguished between groups, we computed effects sizes (Cohen's *d*; vs. HOA) and the average difference (Δ vs. HOA) for each gait modification. To determine whether specific gait modifications were differentiated between groups, we repeated the above analysis for gait modification subclasses (*e.g., swing, simple duple*). Linear models were fit using *fitlm* in MATLAB 2021b (Mathworks Ltd, Natick, USA).

$$\%Error = \beta_0 + \beta_{HYA} \cdot HYA + \beta_{MCI} \cdot MCI + \epsilon \quad (1)$$

3 Results

3.1 Study compliance

Data were collected in 37 participants (12 per group, plus one additional HYA participant). The additional HYA participant was unable to follow directions when performing rhythmic movement sequences and was excluded from analysis. One MCI participant failed to complete the protocol due to fatigue and completed the protocol in a follow-up visit. One MCI participant was only able to complete temporal trials due to fatigue and balance concerns. Across the 36 participants included in analysis, only 8 trials (~1% of all trials) were omitted due to sensor errors not detected during the experiment. Most participants completed the full four walkway lengths of the RMS protocol. Across groups, 24 participants completed four walkway lengths, 10 participants completed two-to-three lengths (5 HOA, 5 MCI), and only two participants (1 HOA, 1 MCI) completed a single walkway length.

3.2 RMS performance was reduced with age

When averaging across gait modifications within each modification class (*spatial*, *temporal*, *spatiotemporal*), regression analysis revealed that the HYA group performed *spatial* gait modifications significantly more accurately than the HOA group ($p = 0.010$; $d = 1.1$, $\Delta = 4.0\%$) (**Figure 3**). HYA participants also performed *spatiotemporal* gait modifications more accurately than HOA participants ($p = 0.048$; $d = 0.8$, $\Delta = 2.1\%$). Conversely, HYA participants did not perform *temporal* gait modifications significantly more accurately than HOA participants.

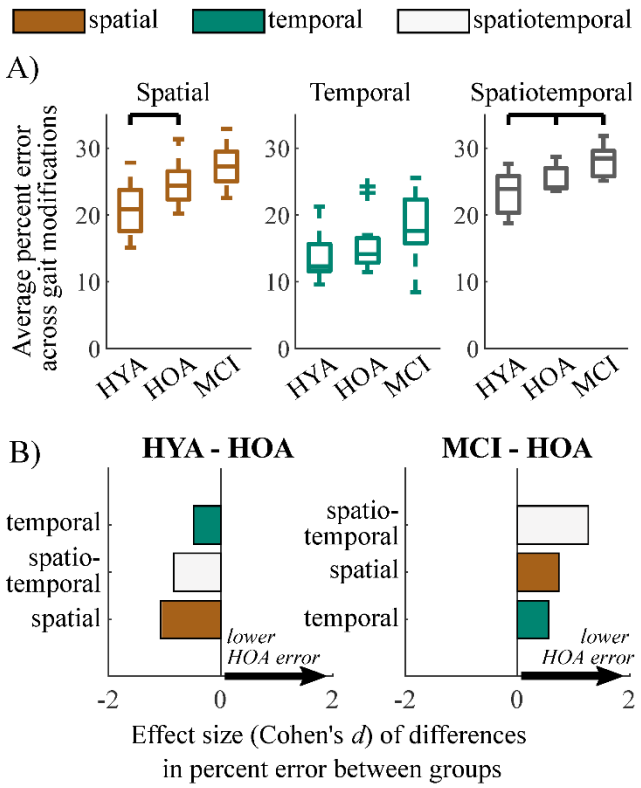


Figure 3: Summary of group performance on gait modifications. A) Boxplots showing group performance on spatial, temporal, and spatiotemporal trials. Each sample consists of the

average percent error relative to target values across nine gait modifications for spatial and temporal trials and four gait modifications for spatiotemporal trials. B) Effect sizes of differences in performance (Cohen's *d*) between HYA and HOA groups (left) and HOA and MCI groups (right) on spatial (orange), temporal (green), and spatiotemporal (white) gait modifications. Positive values (arrows) imply that the HOA group exhibited lower error on gait modifications.

Within movement subclasses (*e.g.*, *swing*, *simple-duple*), differences in spatial performance between the HYA and HOA groups were largest in modifications to the *swing* phase of gait ($p = 0.006$, $d = -1.3$, $\Delta = 5.8\%$) (**Figure 4A & B**). Differences in gait modification performance in both the *stance* phase ($p = 0.074$, $d < 0.8$, $\Delta = 2.2\%$) and the combined *swing-stance* modifications ($p = 0.054$, $d < 0.9$, $\Delta = 2.8\%$) had smaller effects that did not reach significance. In particular, deficits in gait modification accuracy in HOA were largest in *swing*-phase modifications that involved large hip flexion ranges of motion (*i.e.*, *attitude*, *developpé*, and *battement*), with large effect sizes ($p < 0.001$; $d > 0.9$; $\Delta = 4.5\%$). These differences are exemplified by the *attitude-developpé* modification shown in **Figure 4C**.

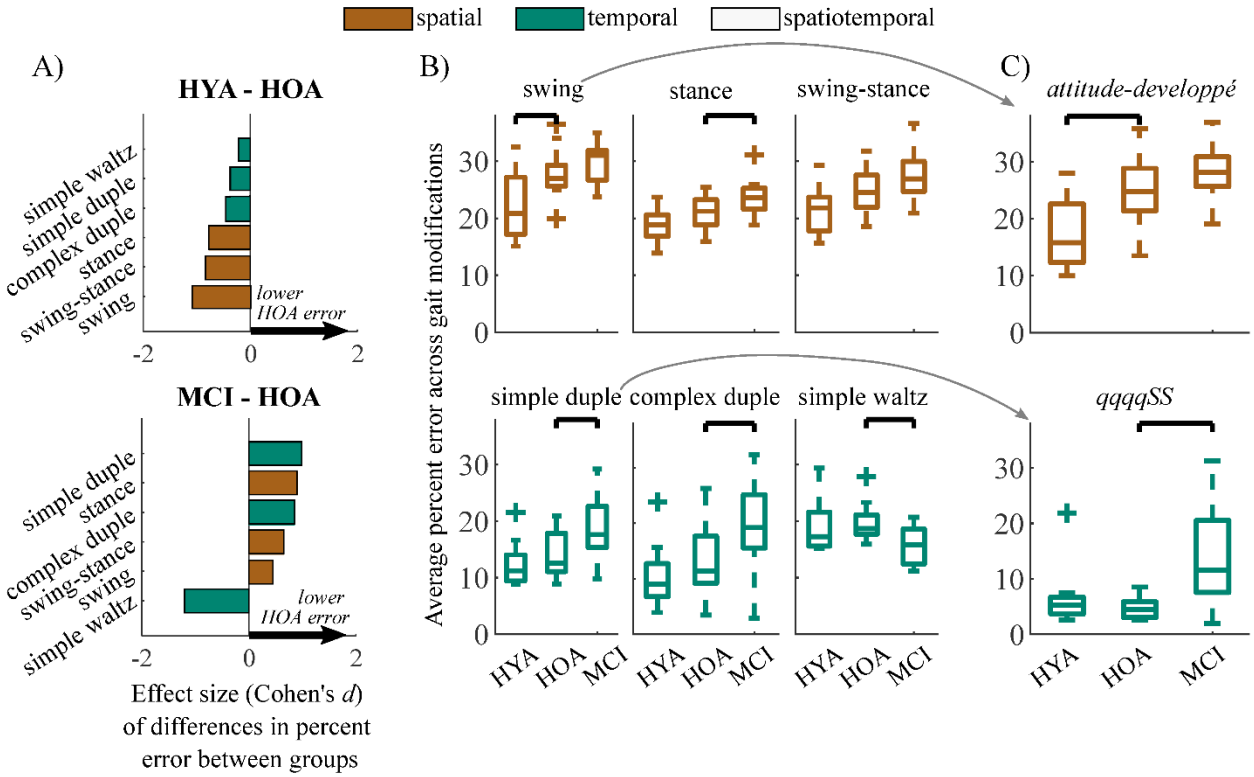


Figure 4: A) Effect sizes of differences in performance (Cohen's *d*) between HYA and HOA groups (top) and HOA and MCI groups (bottom) in each gait modification subclass. Spatial and temporal modifications are denoted in orange and green, respectively. Positive values (arrows) imply that the HOA group exhibited lower error on gait modifications compared to either group. B) Boxplots showing distributions of gait modification accuracy (percent error vs. targets) for spatial (top) and temporal (bottom) gait modifications. C) Results from exemplary participants for gait

modifications that elicited the largest between-group effect sizes. The *attitude-developpé* modification (top) elicited the largest difference in spatial performance between the HYA and HOA groups. The *simple duple* modification, *qqqqSS*, elicited the largest difference in temporal performance between the HOA and MCI groups but did not differentiate between the HYA and HOA groups.

3.3 RMS performance was reduced in older adults with mild cognitive deficits

Unlike differences in the HYA and HOA groups, the HOA group performed only *spatiotemporal* gait modifications significantly more accurately than the MCI group ($p = 0.017$; $d = 1.3$, $\Delta = 2.6\%$; **Figure 3A**). While many participants with MCI exhibited reduced *spatial* and *temporal* modification accuracy compared to the HOA group, these differences did not reach statistical significance. *Temporal* accuracy was highly variable in both groups, with some participants with MCI performing temporal modifications more accurately than those in the HOA group. However, the HOA and MCI groups still exhibited a moderate differential effect size ($p = 0.16$; $d = 0.6$; $\Delta = 2.4\%$).

Differences in *spatiotemporal* modification accuracy were driven by HOA performing the *simple duple* ($p = 0.012$, $d = 1.0$, $\Delta = 4.9\%$), *complex duple* ($p = 0.030$, $d = 0.9$, $\Delta = 6.5\%$), and *stance* ($p = 0.032$, $d = 0.9$, $\Delta = 2.6\%$) gait modifications more accurately than MCI participants (**Figure 4A & B**). An example of group differences in *simple duple* modification accuracy is shown in **Figure 4C**, in which participants with MCI struggled to perform the six-step temporal sequence *qqqqSS*. Surprisingly, the MCI group performed the *waltz* gait modifications significantly more accurately than the HOA group ($p = 0.013$, $d = 1.2$, $\Delta = -4.0\%$).

4 Discussion

This study leveraged biomechanical analysis and music theory to investigate the impacts of age and cognitive function on individuals' abilities to flexibly modulate their gait. By defining biomechanical targets that decoupled common flexion and extension patterns in walking, deficits in the ability of HOA to modulate spatial components of their gait patterns, relative to HYA, we observed an effect of age on the flexibility of spatial features of locomotion, which has previously been demonstrated or hypothesized (Ivanenko et al., 2005; Earhart, 2013). Conversely, defining temporal targets that deviated from the typical symmetric two-step pattern of normal walking, did not reveal significant deficits in the ability of individuals with MCI to modulate gait, relative to HOA. Differences in spatiotemporal gait modification performance both between HYA and HOA and between HOA and MCI suggest that age and cognitive function combine to reduce individuals' abilities to flexibly modulate gait patterns. Further, by testing a broad set of spatial and temporal movement patterns, our novel experimental framework revealed group differences in movement performance that would not be revealed by normal walking or by a single set of gait modifications (e.g., backward walking, fast walking). Given the importance of selecting an appropriate level of challenge during rehabilitation, our findings suggest that both age and cognitive function, as well as movement types, should be considered when designing complex movement, music-movement, or dance-based therapies for individuals with MCI as others have recommended (Guadagnoli and Lee, 2004).

4.1 Motor deficits reduce the ability to accurately modulate spatial gait features

Reduced performance on spatial and spatiotemporal, but not temporal, gait modifications in HOA relative to HYA suggests that declines in motor function with age may limit individuals' abilities to achieve these spatial modifications. Age is associated with reductions in strength and balance (Pijnappels et al., 2008; Reimann et al., 2020), which is consistent with the observed large deficits in

gait modification performance during swing-phase modifications in HOA relative to HYA, which often involved large hip ranges of motion. Additionally, a post-hoc analysis of individual gait modifications revealed that *swing* and *swing-stance* modifications comprised five of the six modifications eliciting the largest difference in performance between HOA and HYA. Consequently, *swing*-phase gait modifications represent a potential framework to both test and train balance capacity in older adults (Bauby and Kuo, 2000; Kuo, 2007). Note that reduced *swing* modification performance contrasts with performance noted during the stance modifications, which challenged strength more than balance because stance modification targets could be achieved during double-limb support.

Age-related declines in strength may impact individuals' abilities to perform plantarflexion during stance (Browne and Franz, 2018): multiple HOA and MCI participants were unable to generate sufficient plantarflexor moments to raise their heel during single-limb support in the *relevé and piqué* stance modifications. Plantarflexor muscle properties are altered and activation capacity is reduced in older adults, which may limit ankle torque production capacity during gait modifications (Morse et al., 2004; Conway and Franz, 2020). Dance-based movements that require plantarflexor moment generation during stance may, therefore, challenge a prominent age-related deficit in HOA.

4.2 Cognitive deficits may reduce the ability to accurately modulate temporal gait features

We observed a moderate effect towards individuals with MCI exhibiting worse performance on temporal gait modifications than those in the HOA group, suggesting that cognitive deficits associated with MCI reduced individuals' abilities to flexibly modulate temporal features of gait. For example, individuals with MCI exhibited worse performance for six-step temporal sequences (vs. 2-step of 4-step sequences), particularly during the *complex duple* modifications. Accurately performing longer sequences places greater demands on working memory, which is reduced in individuals with MCI (see *Reverse Corsi Blocks Test* in **Table 1**) (Vandierendonck et al., 2004; Montero-Odasso et al., 2012). An alternative explanation for poor temporal modification performance is that reduced motor-cognitive integration in individuals with MCI limited participants' abilities to use the musical cues to adopt the proper timing for the assigned movement (Kluger et al., 1997; Hackney et al., 2017).

Waltz modifications represented a surprising case in which individuals with MCI performed modifications more accurately than HOA. Specifically, individuals with MCI performed the *quick-Slow* (*qS*) modification better than HOA (post-hoc analysis: Cohen's $d = 2.8$). *Waltz* sequences were either two- or four-step, reducing their challenge to working memory compared to the six-step *Duple* sequences and possibly making these modifications easier for individuals with MCI (Montero-Odasso et al., 2012). Additionally, the three-count of *Waltz* consisted of one *quick* (*q;* 33% of the stride) and one *Slow* (*S;* 67% of the stride) step in each measure. This division of 33% and 67% of a stride is similar to the approximate percentages of the swing (40%) and stance (60%) phases during normal walking, respectively(Winter, 1984). Consequently, Waltz may have represented a smaller deviation from normal walking, enabling greater automaticity and reduced cortical demand than Duple modifications (Clark, 2015). Increased automaticity, however, would only explain a lack of deficit in *Waltz* performance in individuals with MCI. Better *Waltz* performance in MCI compared to HOA may stem from differences in music or dance experience, which represents an interesting area of future research.

4.3 Motor and cognitive deficits reduced the ability to perform spatiotemporal modifications in individuals with MCI

Large deficits in spatiotemporal performance in individuals with MCI compared to HOA were expected and further emphasize the impacts of cognitive deficits on the ability to voluntarily modulate gait kinematics. Spatiotemporal gait modifications elicited the largest differences in movement performance between HOA and MCI. Motor-cognition is adversely affected with MCI, and the requirement to modulate both spatial and temporal parameters affected those with MCI more than HOA (Hackney et al., 2017). Additionally, reduced set-shifting capacity in MCI compared to HOA - revealed by large differences in the A and B components of the Trail Making Task (Bowie and Harvey, 2006) - may explain reduced spatiotemporal performance in MCI. For example, individuals with MCI may struggle to identify tempos in the music while remembering gait modifications. Participants were instructed to equally prioritize the temporal or spatial components of the spatiotemporal gait modifications. However, some participants in the MCI group reported "giving up" on either the spatial or temporal components of the modifications. Future investigation into which aspects of RMS gait modifications are prioritized with age and cognitive decline may provide further insight into mechanisms impacting specific features of movement performance (Earhart, 2013).

4.4 Clinical implications

Beyond advancing our understanding of how age and cognition impact the ability to flexibly modulate gait, our findings have implications for dance-based therapies for individuals with MCI. Creative dance-based movement therapies aim to challenge both motor and cognitive function and have shown positive impacts on spatial cognition, executive function, balance, and mobility in individuals with Parkinson's and MCI (Hackney et al., 2007a; Hackney et al., 2007b; McKee and Hackney, 2013; Zhu et al., 2020). Our results show that different temporal features of music and spatial components of dance movements will challenge distinct motor (e.g., strength or balance) and cognitive (e.g., working memory, set shifting, or motor-cognitive integration) features (Thom and Clare, 2011; Montero-Odasso et al., 2012; Earhart, 2013; Browne and Franz, 2018). Consequently, personalizing music and dance selections during therapy based on an individual's motor and cognitive function may maximize therapeutic effects. Specifically, selecting music and dance parameters that optimize the challenge point for an individual may maximize benefits while retaining motivation (Hackney et al., 2007a). For example, scaling the spatial components of dance therapies to an individual's motor capacity may be necessary to challenge balance and strength without fatiguing or demotivating the participant. Similarly, our temporally complex rhythms were challenging for individuals with MCI to perform accurately, especially when simultaneously performing spatial modifications. Early stages of therapies may, therefore, benefit from isolated temporal practice before introducing spatial modifications to the movement (Hackney and Earhart, 2010).

4.5 Limitations

The following limitations constrain the generalizability of our findings. First, our modest sample size of twelve participants per group lacked the statistical power to identify all differences in movement performance, particularly during temporal gait modifications. Nonetheless, our data revealed differences in movement performance for spatial and spatiotemporal gait modifications, and showed moderate differential effect sizes (HOA vs. MCI) during temporal modification performance. Second, we did not adjust our analyses to account for differences in music and dance experience. Individuals with more music and dance experience may perceive rhythms more accurately, and individuals with dance experience may exhibit greater capacity to integrate motor commands with perceived rhythms. As some participants reported difficulty in identifying a rhythm during temporal

modifications, music with a more prominent downbeat may mitigate potential effects of music experience on temporal modification performance. Finally, while protocol administrators verified that participants understood each gait modification similarly before collecting data, understanding may have improved over the first few trials, potentially improving performance in later trials. However, we used a block randomization strategy to account for changes in comprehension of the movements.

5 Conclusions

We developed and implemented an innovative RMS gait modifications protocol to evaluate the impacts of age and cognitive function on the ability to accurately modulate spatial and temporal features of gait. By improving our understanding of motor and cognitive impacts of the ability to modulate gait, this study represents an early step toward systematically personalized dance-based movement therapies. Furthermore, this study lays the foundation for future evaluation of the ability of RMS to 1) help diagnose cognitive-motor impairments by providing insight into mechanisms of movement performance deficits and 2) track intervention efficacy by quantifying changes in the accuracy of spatial and temporal features of gait modifications following therapy. Future studies identifying clinical and mechanistic predictors of RMS performance will advance our ability to provide quantitative metrics that assist clinicians in selecting movement therapy parameters to maximize treatment efficacy.

6 Author Contributions

MCR, MHE, JLM, LE, and TMK obtained funding for the study. MHE, TK, LE, MCR, and AS defined the study design and data collection protocol. MCR, AS, and KC were skilled assessors who performed data collection. MHE, JLM, TK, LE, and MCR supervised the study and planned data analysis. MCR and JLM performed data analysis. MCR drafted the original manuscript. All authors provided intellectual critique and manuscript revisions.

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