Associations between music and dance relationships, rhythmic proficiency, and spatiotemporal movement modulation ability in adults with and without mild cognitive impairment

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Running title: Dance, music, and movement ability in MCI

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Abstract

Background: Personalized dance-based movement therapies may improve cognitive and motor function in individuals with mild cognitive impairment (MCI), a precursor to Alzheimer's disease. While age- and MCI-related deficits reduce individuals' abilities to perform dance-like rhythmic movement sequences (RMS)—spatial and temporal modifications to movement—it remains unclear how relationships to dance and music affect the ability to perform RMS.

Objective: Characterize associations between RMS performance and music or dance relationships, as well as the ability to perceive rhythm and meter (rhythmic proficiency) in adults with and without MCI.

Methods: We used wearable inertial sensors to evaluate the ability of 12 young adults (YA; age=23.9±4.2 yrs; 9F), 26 older adults without MCI (OA; age=86.1±8.5 yrs; 16F), and 18 adults with MCI (MCI; age=70.8±6.2 yrs; 10F) to accurately perform spatial, temporal, and spatiotemporal RMS. To quantify self-reported music and dance relationships and rhythmic proficiency, we developed Music (MRQ) and Dance Relationship Questionnaires (DRQ), and a rhythm assessment (RA), respectively. We correlated MRQ, DRQ, and RA scores against RMS performance for each group separately.

Results: The OA and YA groups exhibited better MRQ and RA scores than the MCI group ($p<0.006$). Better MRQ and RA scores were associated with better temporal RMS performance for only the YA and OA groups (r^2=0.18-0.41; $p<0.030$). DRQ scores were not associated with RMS performance in any group.

Conclusions: Cognitive deficits in adults with MCI likely limit the extent to which relationships to music or rhythmic proficiency improve the ability to perform temporal aspects of dance-based therapies.

Introduction

Dance-based movement therapy is a cognitively engaging physical activity that helps mitigate neurodegeneration and improve cognitive and motor function in individuals with mild cognitive impairment (MCI), a precursor to Alzheimer's Disease and dementia [1-5]. The level of motor and cognitive challenge of dance-based therapies may be customized by selecting different therapy parameters (e.g., prescribed dance movements or musical elements). Selecting therapy parameters that challenge each individual, without being discouragingly difficult, may enhance therapeutic efficacy [6]. However, we currently lack objective approaches to personalize dance-based therapy parameters [1, 7]. The ability to perform dance-based therapies likely depends on multiple factors, including aspects of motor and cognitive function, as well as each individual's relationships to music and dance (i.e., histories, experiences, and attitudes towards music and dance) [1, 3, 5, 7]. While we previously showed that age-related declines in motor and cognitive function reduce the ability to perform dance-like movements, it remains unclear how relationships with dance and music, or the ability to perceive and replicate rhythms, impact this ability [8].

Assaying an individual's ability to perform dance-like movements is critical for determining challenging, engaging, and individual-specific dance therapy protocols. We recently developed a library of Rhythmic Movement Sequences (RMS) that isolate spatial (e.g., modified lower-extremity joint range of motion and coordination) and temporal (e.g., modified timing of stepping patterns) features of forward movement (*i.e.*, walking) [8, 9]. RMS consists of three classes of dance-based modifications to forward movement: spatial, temporal, and spatiotemporal, which challenge distinct spatial and temporal aspects of movement performance. RMS may, therefore, be used to probe individuals' abilities to accurately perform rhythmic movements during therapy.

RMS performance can be quantified as the ability to achieve prescribed spatial and temporal targets [8]. Spatial RMS consist of movement modifications to achieve prescribed kinematic (i.e., joint angle) targets, with no prescribed changes in step timing [10]. Deviations from spatial RMS targets may reflect an inability to recall or understand spatial patterns and execute appropriate motor commands to modulate spatial aspects of movement. Temporal RMS involve performing prescribed patterns of quick and slow steps, synchronized to perceived concurrent rhythmic cues in music, with no prescribed spatial modifications [9]. Deviations from the prescribed tempo or step pattern reflect an inability to perceive musical cues and recall or execute stepping patterns. Spatiotemporal RMS assays the additional challenge of simultaneously performing spatial and temporal RMS. Because the RMS classes differentially challenge aspects of motor and cognitive function, and are influenced by experience perceiving rhythms and executing motor commands, RMS performance may reveal how relationships to music and dance and rhythmic proficiency impact the ability to perform dance-based therapies.

We previously showed detrimental effects of age-related declines in motor function and MCI-related declines in cognitive function on individuals' abilities to perform RMS [8]. Worse performance on only spatial and spatiotemporal RMS in older adults without MCI, compared to young adults, suggests that age-related motor deficits are primarily related to a reduced ability to accurately modulate spatial features of movement. Conversely, worse performance on only spatiotemporal and some temporal RMS in older adults with MCI, compared to older adults without MCI, suggests that cognitive deficits in adults with MCI are related to a reduced ability to accurately perform both spatial and temporal features of movement. However, RMS performance was variable, even between individuals of similar age and cognitive status. Relationships to music and dance, or the ability to perceive meter and rhythm and synchronize motor commands to music, may help explain variability in RMS performance in individuals of similar age and cognitive status [11].

Merely by existing within a cultural context and through past experiences, individuals develop diverse perceptions, attitudes, and histories towards music and dance that constitute their "relationship" with each of these ubiquitous and often-interconnected art forms [11, 12]. These relationships may influence the ability to perform dance-like movements. Stronger relationships with music may enhance the ability to perceive and predict the rhythmic patterns, musical groupings, and meter needed to follow temporal movement cues in music [13]. Stronger relationships with dance may enhance the ability to sense and accurately modify joint kinematics and entrain movements to musical cues. Conversely, stronger rhythmic proficiency reflects a better ability to perceive rhythms, anticipate beats in music, and entrain motor commands to prescribed rhythmic cues [11]. Rhythmic proficiency, therefore, reflects perceptual acuity and skill pertinent to RMS performance, making it distinct from music and dance relationships [14].

Here, we investigated how individuals' relationships with dance and music, and their rhythmic proficiency impacted their performance on spatial, temporal, and spatiotemporal RMS. The central hypothesis of this work is that stronger relationships and past experiences with music and dance, and rhythmic proficiency, contribute to an improved ability to accurately modulate spatial and temporal aspects of movement during RMS. To test this hypothesis, we developed Music Relationship (MRQ) and Dance Relationship Questionnaires (DRQ) that evaluate individuals' relationships to music and dance, respectively. We also developed a Rhythm Assessment (RA) that evaluates rhythmic proficiency. We compared these novel assessment scores to RMS performance in younger adults (YA) and older adults without (OA) and with MCI (MCI). We predicted that, within each group, stronger relationships to music (higher MRQ scores) would be associated with more accurate performance of temporal and spatiotemporal RMS. We similarly predicted that, within groups, stronger relationships to dance (higher DRQ scores) would be associated with more accurate performance of spatial and spatiotemporal RMS. Finally, we predicted that better rhythmic proficiency (higher RA scores) would be associated with more accurate performance of temporal and spatiotemporal RMS.

Materials and Methods

This study was approved by the Emory Institutional Review Board (STUDY00003507). All participants provided written, informed consent before participation.

Participants

An observational cross-sectional study with 56 participants was performed in non-disabled younger adults (YA; N=12), older adults without MCI (OA; N = 26), and older adults with MCI (N = 18;
Table **1**). The inclusion criteria for all participants were the ability to walk 20m without an assistive device, 6 years of education or good work history, proficiency in the English language, and no hospitalizations in the last 60 days. YA participants included in the study were 18-35 years of age and OA and MCI participants were 55 years and older. For participants with MCI, additional inclusion criteria included amnestic MCI, as defined using the Alzheimer's Disease Neuroimaging Initiative criteria and standard clinical assessments showing reduced executive function, working memory, and spatial cognition [15]. Assessments characterizing cognitive function included the Montreal Cognitive Assessment (MoCA), Reverse Corsi Blocks, Body Position Spatial Task, and Trail Making Test (
Table **1**) [16-19].
Table **1** shows the average (±1 SD) participant demographic information and clinical assessment scores for each group, along with p-values reflecting the probability of statistical differences across the groups (omnibus ANOVA or Chi-Squared tests, where appropriate). Demographic and clinical characteristics can be found in
Table 1.

Table 1: Demographic characteristics for each participant group.

	YA	**OA**	**MCI**	**p-value***
N	12	26	18	
Age*,†				< 0.01
Mean (SD)	23.9 (4.2)	68.1 (8.5)	70.8 (6.2)	
Range	18.0 – 30.0	53.0 – 85.0	57.0 - 79.0	
Height (m)				0.14
Mean (SD)	1.65 (0.09)	1.73 (0.13)	1.69 (0.09)	
Range	1.57 – 1.91	1.56 - 2.07	1.52 - 1.83	
Mass (kg)*,†				0.03
Mean (SD)	62.5 (12.7)	73.1 (15.1)	76.3 (13.6)	
Range	49.9 – 90.7	51.7 - 100.0	52.6 - 108.9	
Sex				0.55
F	9 (75%)	16 (62%)	10 (56%)	
M	3 (25%)	10 (38%)	8 (44%)	
Years since MCI[a]				-
	-	-	2.7 (1.9)	

	-	-	0.0-7.0	
Montreal Cognitive Assessment (MoCA)[b,*,‡]				< 0.01
Mean (SD)	28.4 (2.2)	27.4 (2.3)	24.8 (3.6)	
Range	22.0 – 30.0	23.0 - 30.0	18.0 - 30.0	
Reverse Corsi Blocks[c,*,†,‡]				< 0.01
Mean (SD)	59.6 (21.2)	37.3 (14.7)	27.4 (14.2)	
Range	15.0 – 98.0	20.0 - 77.0	12.0 - 54.0	
Body Position Spatial Task[d,*,†]				< 0.01
Mean (SD)	31.2 (15.5)	17.4 (7.9)	14.0 (6.0)	
Range	12.0 – 70.0	6.0 - 35.0	4.0 - 25.0	
Trail Making Test (B-A)[e,*,‡]				0.03
Mean (SD)	24.3 (13.9)	29.7 (21.6)	44.9 (26.0)	
Range	7.9-50.4	-28.6 – 68.4	-19.7 – 92.5	

Abbreviations: N, number of participants; YA, younger adults; OA, older adults without mild cognitive impairment; MCI, older adults with mild cognitive impairment; m, meters; kg, kilograms; SD, standard deviation; F, female; M, male.

*Significant between-group differences (omnibus ANOVA or Chi-Squared tests, where appropriate; $\alpha = 0.05$).

†Significant differences between the YA and OA groups (post-hoc independent-samples t-tests; $\alpha = 0.05$).

‡Significant differences between the OA and MCI groups (post-hoc independent-samples t-tests; $\alpha = 0.05$).

Superscript letters denote the number of missing participants for each analysis: [a]N = 13 (MCI group only); [b]N = 55; [c]N = 54, [d]N = 52, [e]N = 53.

We did not test for differences between the YA and MCI groups.

RMS modifications

Participants performed an overground assessment battery of 9 *spatial*, 9 *temporal*, and 4 *spatiotemporal* RMS patterns, using the same protocol as described by Rosenberg and colleagues (2023) [8]. Spatial modifications involved modulating leg joint angles during the stance or swing phases during forward movement (i.e., walking), or during both phases of gait. Spatial modifications did not prescribe step timing or rhythms. The spatial modifications used in this study have corollaries in ballet, alter the typical leg joint flexion-extension patterns of walking, and were designed to be feasible for OA and individuals with MCI [20]. We defined three sub-classes of spatial modifications: *swing*, *stance*, and *swing-stance* modifications, with three different modification trials per sub-class (Figure 1A). For *swing* and *stance* modifications, a different movement was performed by each leg. For *swing-stance* modifications, two different movements were performed by the left leg, while the right leg could move freely.

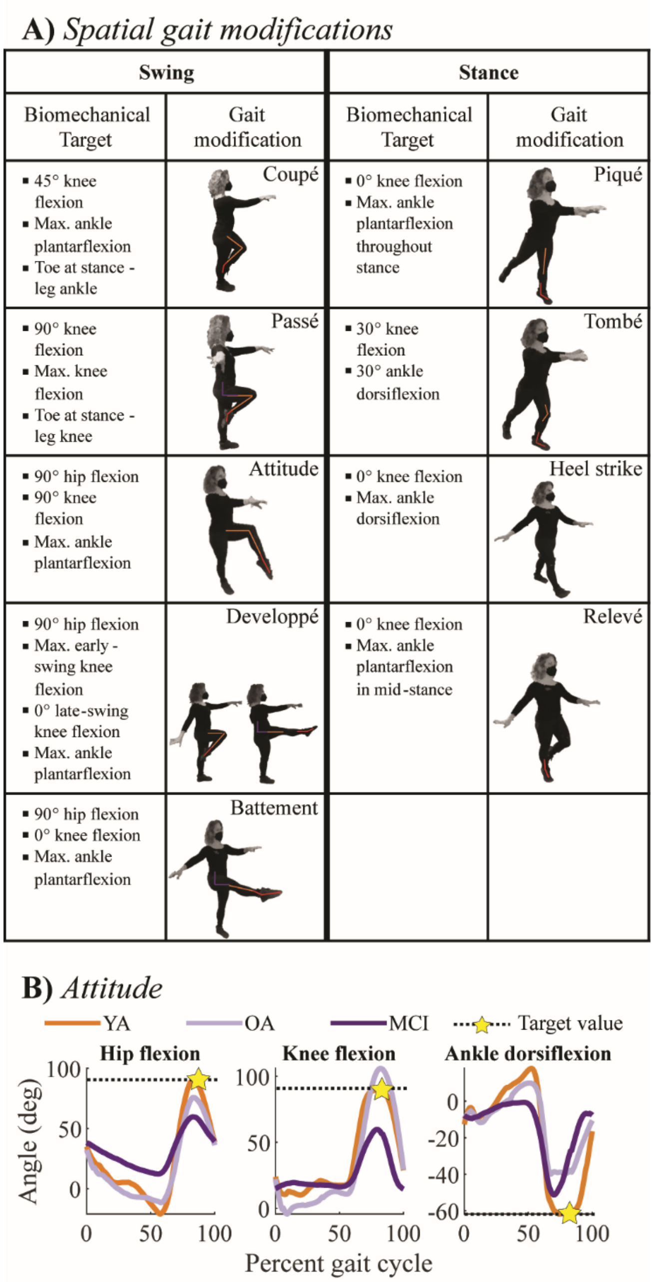
A) Spatial gait modifications
Swing
Stance
Biomechanical Target
Gait modification
Biomechanical Target
Gait modification
▪ 45° knee flexion ▪ Max. ankle plantarflexion ▪ Toe at stance - leg ankle
Coupé
▪ 0° knee flexion ▪ Max. ankle plantarflexion throughout stance
Piqué
▪ 90° knee flexion ▪ Max. knee 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
YA
OA
MCI
Target value
Hip flexion
Knee flexion
Ankle dorsiflexion
Angle (deg)
Percent gait cycle
100
50
0
-20
-40
-60

Figure 1: **Spatial modifications and biomechanical targets used in spatial and spatiotemporal rhythmic movement sequences (RMS)**. A) Spatial modifications. The left two columns correspond to modifications to swing-phase kinematics during movement, while the right two columns correspond to modifications to stance-phase kinematics. The bullets describe each biomechanical target variable for the corresponding modification. Deviations from these target values quantified RMS performance. The colored lines denote the hip (purple), knee (orange), and ankle (red) biomechanical targets. B) An example of biomechanical targets for the *Attitude* RMS modification. Each plot shows kinematics for one joint during this modification. On each plot, the dashed lines denote the corresponding biomechanical target value. Gold stars denote the portion of the stride (e.g., swing vs. stance) where the joint angles were compared to target values. Colored lines denote example YA (orange), OA (gray), and MCI (purple) participants. *Re-used, with permission, from Rosenberg et al., 2023 [8]*.

Temporal modifications involved walking while performing repeating sequences of 2-6 half (&), quick (q), and slow (S) steps synchronized to external rhythmic cues, without constraints on the spatial aspects of movement [8]. Half steps spanned half of a beat (*&* in Figure 2), quick steps spanned one beat (solid note in Figure 2), and slow steps spanned two beats (open note in Figure 2). Temporal modifications were grounded in principles of music theory that suggest that auditory cues can influence the temporal progression of movement [11, 21, 22]. We defined three subclasses of temporal modifications from ballroom dance: *simple duple* (2-count), *complex duple* (2-count), and *waltz* (3-count), shown in Figure 2. Each class was expected to challenge different aspects of Western music listeners' experiences [8, 11]. Participants performed duple and waltz modifications synchronously to modified versions of Libertango (by Astor Piazzolla, 1974) and Waltz No. 2 (by Dmitri Shostakovich, 1938), respectively, with superfluous accents and cues removed [8, 23]. All participants performed the duple modifications at 100 beats per minute (bpm). For the waltz modifications, the YA groups performed modifications to music at 80 bpm, while the music was slowed to 60 bpm for the OA and MCI groups to ensure that they could perform the modifications. The faster beat used in the YA group was not found to decrease RMS performance relative to the other groups [8].

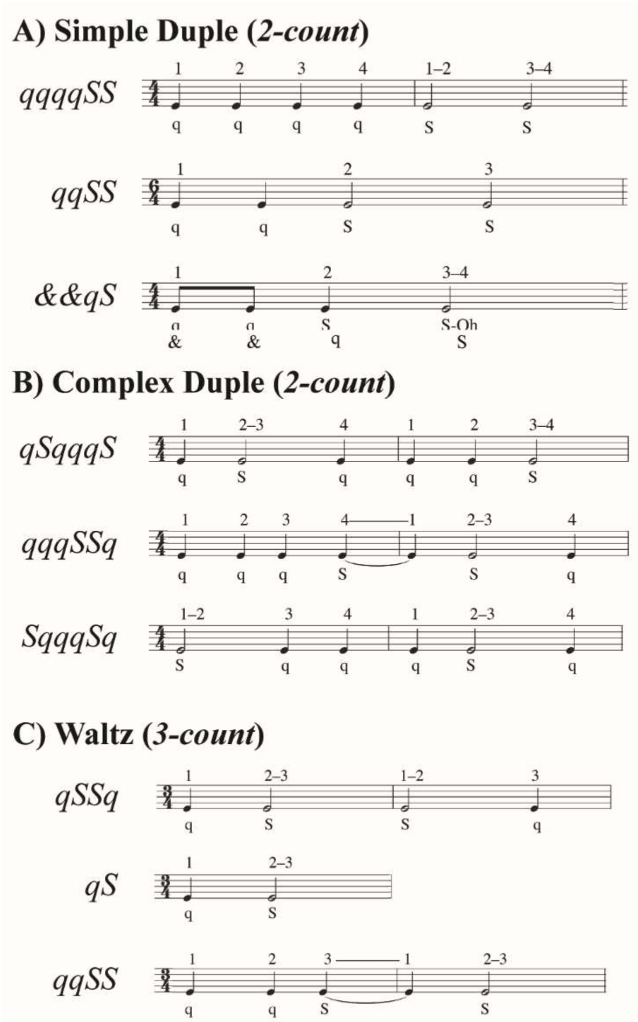

Figure 2: **Rhythmic stepping sequences used in temporal and spatiotemporal rhythmic movement sequence (RMS) modifications**. Each sequence consisted of 2-6 steps, synchronized to either a duple (2-count) or waltz (3-count) meter. Sequences were comprised of very-quick (*&* = half-beat per step), quick (*q* = one beat per step), and slow (*S* = two beats per step) steps. The numbers above each musical note reflect the beat count. A) Simple duple sequences were two-count rhythms with the strong beat on the downbeat and spanned 1-2 measures. B) Complex duple sequences were also two-count rhythms with a weak beat on the downbeat and spanned 2 measures. C) Waltz sequences were three-count rhythms spanning 1-2 measures. *Re-used, with permission, from Rosenberg et al., 2023 [8].*

Each spatiotemporal sequence involved performing spatial and temporal modifications concurrently. Participants performed four spatiotemporal modifications consisting of different combinations of two spatial modifications and one temporal modification (Figure 1 & Figure **2**).

Trial order was block-randomized for each participant. *Spatial* or *temporal* modifications were randomly selected to be performed first and second, followed by *spatiotemporal* modifications. Within each RMS class (*spatial*, *temporal*, *spatiotemporal*), the order of modification sub-classes was randomized, as was the order of the three modifications within each subclass.

RMS protocol

For each RMS modification, YA performed RMS while walking overground for four lengths of an 11-meter walkway. To mitigate the effects of fatigue on RMS performance, participants in the OA and MCI groups performed modifications for at least 11 meters (1 walkway length) [8]. Participants who walked shorter distances also took more strides per walkway length. All participants performed each modification for at least 15 strides.

During RMS assessments, sagittal-plane hip, knee, and ankle kinematics were recorded using Opal V2R inertial measurement units (APDM, Inc., Portland, USA). Fifteen sensors were attached to the forehead, sternum, lumbar region and bilaterally to the hands, wrists, upper arms, thighs, shanks, and feet in a standard configuration [24]. For each trial, joint kinematics were estimated using validated proprietary software (APDM Moveo Explorer) [25].

Before performing each spatial modification, participants watched a tutorial video of the sequence being performed by an expert and received instructions on how to achieve the biomechanical targets of the movement (Figure 1A) [8]. Before performing each temporal modification, participants watched a tutorial video that guided progressive entrainment of the trial's rhythmic pattern in five steps of increasing complexity: clapping, tapping with one foot, shifting weight between the feet, marching in place, and walking to the rhythmic pattern [26]. Before performing each spatiotemporal modification, participants were reminded of the biomechanical targets (spatial) and step sequences (temporal) and could review practice videos if needed. Participants practiced each RMS modification with assessor feedback until the assessor determined that the participant understood the modification. Practice typically spanned less than one walkway length. At the beginning of each walkway length during temporal trials, the assessor would clap the rhythm for two sequences to help participants identify the rhythm.

RMS performance targets and quantification

Performance of each RMS modification was quantified as each participant's ability to achieve pre-defined biomechanical (spatial and spatiotemporal modifications) and temporal targets (temporal and spatiotemporal modifications). Biomechanical targets were defined by sagittal-plane joint angles of the hip, knee, and/or ankle in the stance or swing phases for each modification (Figure 1A). For example, *attitude* involved biomechanical targets of 90-degree hip flexion, 90-degree knee flexion, and maximal ankle plantarflexion (Figure 1B; stars denote target values).

Temporal targets for each modification were defined by the modification's pattern of quick and slow steps and the prescribed tempos (Figure 2). For example, the *simple duple – qqSS* modification (Figure 2A) involved performing two quick steps, followed by two slow steps at cadences of 100 steps per minute for the quick steps and 50 steps per minute for the slow steps.

RMS performance was defined as the percent error relative to the biomechanical and temporal targets of each trial. For each modification, percent errors were computed for the modification's target variables (Figure 1B), then the error across variables was averaged. For modification classes (spatial, temporal, spatiotemporal), percent errors for each modification within the corresponding class were averaged. Lower spatial or temporal percent error implied better performance on RMS.

Music and dance relationships and proficiency assessments

To quantify individuals' relationships to music, including their prior experiences and how they interact with music in daily life, we developed a Music Relationship Questionnaire (MRQ; Table 2) [27]. The MRQ was administered via REDCap and consisted of ten introspective questions on a Likert scale with seven response categories. A composite MRQ score was defined as the average score of the ten Likert scale questions, producing a maximum possible score of 7, with larger scores reflecting stronger relationships to music.

Table 2: List of questions asked for the Music Relationships Questionnaire (MRQ) and Dance Relationship Questionnaire (DRQ).

Item	MRQ	DRQ	Scoring Scale**
1	Music is important in my life.	Dance is important in my life.	Strongly disagree = 1 Strongly agree = 7
2	I listen to music in my typical day.	I dance in my typical day.*	Strongly disagree = 1 Strongly agree = 7
3	I focus on what I am hearing while listening to music.	While listening to music, I often physically respond (ex: tapping, moving, clapping, nodding, snapping).	Strongly disagree = 1 Strongly agree = 7
4	I focus on other things while music is playing.	I do not often move while music is playing.	Strongly agree = 1 Strongly disagree = 7
5	I actively choose the music I listen to.	I actively choose to move when music is playing.	Strongly disagree = 1 Strongly agree = 7
6	I usually listen to whatever music happens to be playing.	I usually dance to whatever music happens to be playing.	Strongly disagree = 1 Strongly agree = 7
7	I play an instrument/sing.	I dance regularly.	Strongly disagree = 1 Strongly agree = 7
8	I have played an instrument/sung for most of my life.	I have danced for most of my life.	Strongly disagree = 1 Strongly agree = 7
9	I played an instrument/sang only as a child.	I danced only as a child.	Strongly disagree = 1 Strongly agree = 7
10	In a typical day, I play an instrument/sing.	In a typical day, I dance.*	Strongly disagree = 1 Strongly agree = 7

*Two items that were worded similarly and highly correlated (Pearson's r = 0.89) were averaged before computing the composite score for the DRQ.
**The Scoring Scale was identical for the MRQ and DRQ. Note that the Scoring Scale on Item 4 is reversed relative to all other items.

Similarly, to quantify individuals' relationships to dance, including their prior experience and how they interact with dance in daily life, we developed a Dance Relationship Questionnaire (DRQ; Table 2) [27]. The DRQ was administered via REDCap and consisted of ten introspective questions on a Likert scale with seven response categories. Like the MRQ, a composite DRQ score was initially defined as the average score of the 10 Likert scale questions, producing a maximum possible score of 7, with larger scores reflecting stronger relationships to dance. However, because questions 2 and 10 were similarly worded and responses were strongly correlated (Pearson's r = 0.89), we took the average of these questions before computing the composite score across all questions.

To quantify individuals' proficiency in perceiving rhythms and executing motor commands in-sync with those rhythms, we developed an objective rhythm assessment (RA; Table 3) [27]. The RA was conducted in-person or virtually by trained personnel and took 10-15 minutes to complete. The assessment consisted of three parts: 1) To assess participants' abilities to perceive, comprehend, and replicate rhythmic patterns from *auditory* stimuli, participants listened to four recordings of rhythmic patterns of quick and slow claps (listen three times per pattern), then attempted to accurately clap each rhythm twice (Table 3; items 1-4). 2) To assess participants' abilities to perceive, comprehend, and replicate rhythmic patterns from *visual* stimuli, participants read two measures of Western music notation in 4/4 time and attempted to accurately clapback the rhythm (Table 3; item 5). Participants could practice the rhythms for up to one minute before their clapping was scored and were instructed to clap the rhythm even if they could not read musical notation. The audio of all clapped rhythms was recorded for scoring. 3) To assess participants' abilities to recognize different meters in music, participants listened to five music passages, then identified whether that passage consisted of either "two's" (*duple*), "three's" (*triple*), or "other" meters (Table 3; items 6-10). All passages were less than 60 seconds in length and played up to three times for the participant. The RA was scored out of 10 points as described in Table 3. RA instructions are provided in *Supplemental – S1*.

The RA assessment and audio recordings (*RhythmAssessment.pptx*), along with the data (*Table_Data.csv*) used in this manuscript and a data dictionary, are freely available in the supplemental materials.

Table 3: Description of assessment items in the Rhythm Assessment (RA).

Item	Item Description	Scoring Scale – Response (Points)		
1	Auditory A	Correct (1)	Partial (0.5)	Incorrect (0)

2	Auditory B			
3	Auditory C			
4	Auditory D			
5	Visual A			
6	Meter recognition A (Duple)	Duple (1)	Waltz (0)	Other (0)
7	Meter recognition B (Waltz)	Duple (0)	Waltz (1)	Other (0)
8	Meter recognition C (Duple)	Duple (1)	Waltz (0)	Other (0)
9	Meter recognition D (Waltz)	Duple (0)	Waltz (1)	Other (0)
10	Meter recognition E (Other)	Duple (0)	Waltz (0)	Other (1)

"Partially correct" indicated that the participant clapped the rhythm correctly once and incorrectly once.
Auditory items involved listening to a rhythm, then clapping it back.
The *Visual* item involved reading a sequence of 10 musical notes (quarter, half, and full beats) then clapping the notes.
Meter recognition items involved listening to a rhythm, then identifying whether the meter was "*twos" (two-count)*, "*threes" (three-count)*, or "*other*."

Statistical analysis

To determine if groups differed in their experiences with dance and music, as well as their rhythmic proficiency, we tested for differences in MRQ, DRQ, and RA scores between all pairs of groups (YA, OA, and MCI) using independent-sample t-tests ($\alpha = 0.05$). Because our sample was larger than that in [8] and [27], we replicated the study's group-wise comparisons of spatial, temporal, and spatiotemporal RMS performance using independent-sample t-tests ($\alpha = 0.05$). Note that we only compared RMS performance between YA and OA (age effect) and between OA and MCI (cognitive status effect).

To determine if, within each participant group (YA, OA, and MCI), stronger relationships to music (higher MRQ scores) were associated with better temporal modulation ability (lower RMS performance error), we performed linear regression between MRQ composite scores and temporal RMS performance separately for each group. Analyzing groups separately was based on our prior finding that RMS performance differed between groups [8]. Similarly, to determine if, within groups, stronger relationships to music were associated with better spatiotemporal modulation ability, we performed linear regression between MRQ composite scores and spatiotemporal RMS performance.

To determine if, within groups, stronger relationships to dance (higher DRQ composite scores) were associated with better spatial modulation ability, we performed linear regression between DRQ composite scores and spatial RMS performance. Similarly, to determine if, within groups, stronger relationships to dance were associated with better spatiotemporal RMS performance, we performed linear regression between DRQ scores and spatiotemporal RMS performance.

Similarly to the MRQ, to determine if stronger rhythmic proficiency (higher RA composite scores) was associated with better temporal and spatiotemporal modulation ability, we performed linear regression between RA composite scores and RMS performance for temporal and spatiotemporal modifications, respectively, for each group separately.

For all analyses, we report regression accuracy as coefficients of determination (r^2), regression slopes, and significance levels according to Wald tests ($\alpha = 0.05$). Group-level comparisons of demographics and clinical characteristics were performed using the software package *R*. Regression analyses were performed using MATLAB 2021b (Mathworks, Natick, USA).

Results:

Clinical assessments suggest worse cognitive function in adults with MCI, compared to older adults

Clinical assessments revealed group-level differences in motor-cognitive and cognitive function (Table 1). Compared to the OA group, the YA group exhibited better performance on assessments of working memory (Reverse Corsi Blocks; $p < 0.001$) and motor-cognitive integration (Body Position Spatial Task; $p < 0.001$). Conversely, the MCI group exhibited worse performance than the OA group on assessments of global cognitive function (MoCA; $p = 0.005$), working memory (Reverse Corsi Blocks; $p = 0.035$), and set-shifting (Trail Making Test; $p = 0.050$).

Music relationships, rhythmic proficiency, and RMS performance differed between groups

Relationships to music and rhythmic proficiency differed between groups (Figure 3A). The YA and OA groups exhibited stronger relationships to music and greater rhythmic proficiency than the MCI group: On the MRQ, the YA group scored an average of 1.0 point (out of 7) higher ($p = 0.001$) and the OA group scored 0.7 points higher ($p = 0.006$) than the MCI group. The YA and OA groups exhibited similar relationships to music, as indicated by similar MRQ scores ($p = 0.228$). On the RA, the YA group scored an average of 3.2 points (out of 10) higher ($p < 0.001$) and the OA group scored 2.4 points higher ($p < 0.001$) compared to the MCI group. YA and OA groups exhibited similar levels of rhythmic proficiency, as indicated by similar RA scores ($p = 0.223$). No groups exhibited differences in the strength of their dance relationships, as indicated by similar DRQ scores ($p > 0.575$).

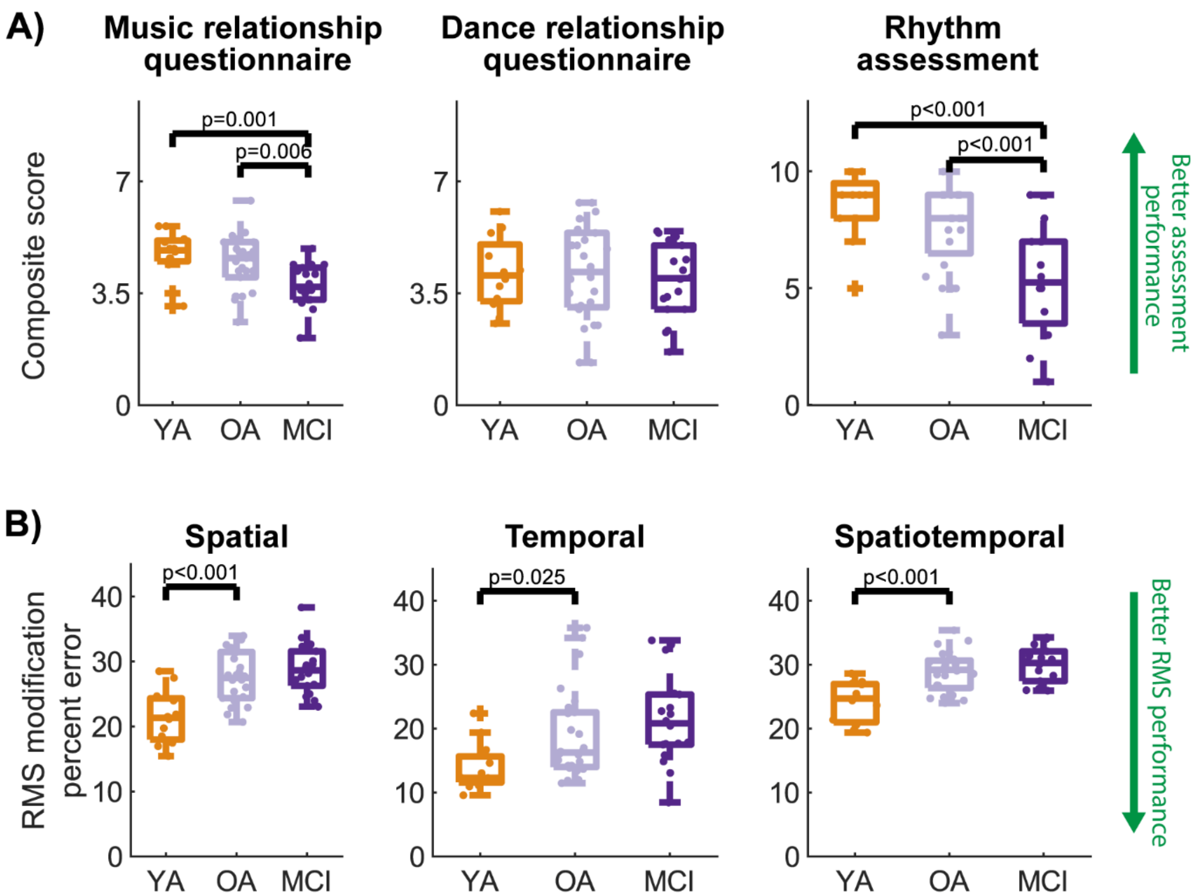

Figure 3: Boxplots representing distributions of Music Relationship Questionnaire (MRQ), Dance Relationship Questionnaire (DRQ), and Rhythm Assessment (RA) scores. A) MRQ, DRQ, and RA scores for the three participant groups (YA, OA, MCI). Higher MRQ and DRQ scores (max = 7) reflect stronger music and dance relationships, respectively. Higher RA scores (max = 10) reflect greater rhythmic proficiency. B) RMS performance error on each of spatial, temporal, and spatiotemporal RMS modifications for the three participant groups. For both plots, dots represent individual participants. Higher composite scores indicate better performance on the MRQ, DRQ, and RA (upper green arrow). Lower RMS error indicates better performance on RMS modifications (lower green arrow). Each spatial and temporal RMS error was averaged across 9 modifications from their respective domains and spatiotemporal error was averaged across 4 modifications. For all boxplots, p-values denote significant differences according to independent-samples t-tests ($\alpha = 0.05$).

Compared to OA, the YA group exhibited better performance, as indicated by lower percent error on spatial ($p < 0.001$), temporal ($p = 0.025$), and spatiotemporal ($p < 0.001$) RMS (Figure 3B). The OA group did not perform RMS modifications with different accuracy than the MCI group (all $p > 0.257$).

Higher MRQ scores were associated with reduced temporal RMS errors in young and older adults without MCI

In participants without MCI, individuals with higher MRQ scores (stronger music relationships) exhibited lower error on temporal RMS (i.e., better temporal RMS performance). MRQ scores were associated with temporal RMS errors in the YA ($r^2 = 0.41$; slope = -3.2; $p = 0.026$; orange in Figure 4A, top) and OA groups ($r^2 = 0.18$; slope = -3.5; $p = 0.030$; grey in Figure 4A, top), explaining a small-to-moderate amount of the variance in temporal RMS errors. Conversely, the MCI group did not exhibit significant associations between MRQ scores and temporal RMS performance ($r^2 = 0.06$; $p = 0.314$; purple in Figure 4A, top). No group exhibited significant associations between MRQ scores and spatiotemporal RMS performance (all $r^2 < 0.15$; $p > 0.114$; Table 4; Figure 4A, bottom).

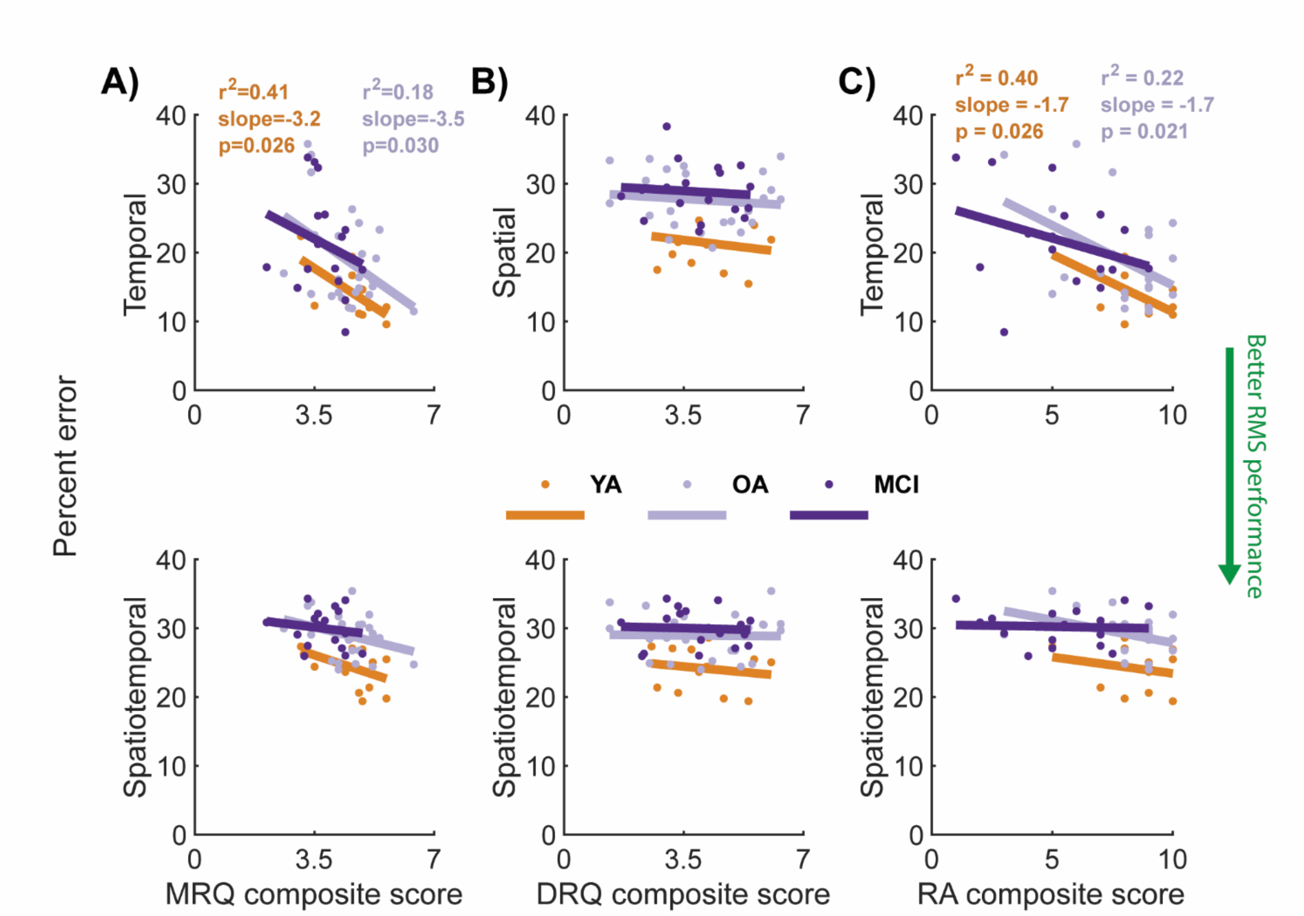

Figure 4: Linear regression testing for within-group associations between RMS performance and each of the MRQ, DRQ, and RA. Each dot represents a single participant. Lines indicate within-group linear fits. Colors denote the groups (YA: orange, OA: gray, MCI: purple). Regression R-squared values, slopes, and p-values are shown on the corresponding plots for fits that were significantly different from zero (Wald tests; $\alpha = 0.05$), with colors corresponding to groups. Each of the spatial and temporal RMS percent errors were averaged across the 9 respective RMS modifications and spatiotemporal errors were averaged across 4 modifications. Lower RMS error indicates better performance (green arrow), on average, across modifications within the corresponding modification class. A) MRQ vs. temporal (top) and spatiotemporal (bottom) RMS performance errors. Higher MRQ scores represent stronger music relationships. B) DRQ vs. spatial (top) and spatiotemporal (bottom) RMS performance errors. Higher DRQ scores represent stronger dance relationships. C) Comparisons of RA with percent errors on temporal (top) and spatiotemporal (bottom) RMS. Higher RA scores imply greater rhythmic proficiency.

Table 4: Univariate linear regression results.

Questionnaire	RMS class	YA			OA			MCI		
		r^2	slope	p	r^2	slope	p	r^2	slope	p

MRQ	**Temporal**	0.41	-3.21	**0.026**	0.18	-3.49	**0.030**	0.06	-2.62	0.317
	Spatiotemporal	0.15	-1.63	0.215	0.10	-1.23	0.114	0.02	-0.62	0.551
DRQ	**Spatial**	0.03	-0.60	0.610	0.01	-0.30	0.575	0.01	-0.29	0.732
	Spatiotemporal	0.03	-0.47	0.612	0.00	-0.03	0.942	0.00	-0.12	0.841
RA	**Temporal**	0.40	-1.67	**0.026**	0.22	-1.74	**0.021**	0.11	-1.01	0.210
	Spatiotemporal	0.05	-0.48	0.498	0.16	-0.66	0.055	0.00	-0.06	0.848

Abbreviations: YA, younger adults; OA, older adults without mild cognitive impairment; MCI, older adults with mild cognitive impairment; RMS, Rhythmic Movement Sequence; MRQ, Music Relationship Questionnaire; DRQ, Dance Relationship Questionnaire; RA, Rhythm Assessment;
For each group, regression results are shown using the coefficient of determination (r^2), regression slope, and p-value (p) denoting a slope that is significantly different from zero ($\alpha = 0.05$). Bold p-values denote $p < 0.05$.

DRQ scores were not associated with spatial or spatiotemporal RMS errors

No group exhibited significant associations between DRQ scores and spatial or spatiotemporal RMS performance (all $r^2 < 0.03$; $p > 0.575$; Figure 4B; Table 4).

Higher RA scores were associated with reduced temporal RMS errors in young and older adults without MCI

In participants without MCI, individuals with higher RA scores tended to exhibit better temporal RMS performance (i.e., lower error). Negative associations between RA scores and temporal RMS error were observed in the YA ($r^2 = 0.40$; slope = -1.7; $p = 0.026$; orange in Figure 4C, top) and OA groups ($r^2 = 0.22$; slope = -1.7; $p = 0.021$; grey in Figure 4C, top), explaining a small-to-moderate amount of variance in temporal RMS errors. Conversely, the MCI group did not exhibit significant associations between RA scores and temporal RMS performance, in part due to heterogeneity in RMS performance across individuals with low RA scores ($r^2 = 0.11$; $p = 0.210$; purple in Figure 4C, top). No group exhibited significant associations between RA scores and spatiotemporal RMS performance (all $r^2 < 0.16$; $p > 0.231$; Table 4; Figure 4C, bottom).

Discussion

This study shows that in young and older adults without MCI, stronger relationships to music and better rhythmic proficiency are associated with a better ability to accurately modulate temporal aspects of movement during RMS. Conversely, cognitive deficits in adults with MCI likely contribute to reduced rhythmic proficiency and hinder the ability to transform relationships to music or rhythmic proficiency into an ability to modulate temporal aspects of movement during RMS. Our central hypothesis was supported only for temporal RMS, as stronger relationships to dance were not associated with an improved ability to perform RMS involving spatial modifications to movement in any group. Neither stronger relationships to music or dance, nor rhythmic proficiency were associated with improved abilities to modulate spatial or spatiotemporal aspects of movement. These findings suggest that only in the absence of MCI-related cognitive deficits will individuals' relationships to music or rhythmic proficiency be useful in informing the selection of musical rhythms in dance-based therapies [5, 6].

Stronger relationships to music and rhythmic proficiency indicate a better ability to accurately modulate temporal features of movement during RMS in adults without MCI, but not with MCI. In adults without MCI, these associations suggest that constructs that are developed by prior relationships to music and support rhythmic proficiency also improve the ability to perceive rhythm and meter and entrain movement to these rhythms. For example, people with stronger music relationships may exhibit more precise communication of temporal stimuli between auditory processing and motor planning regions in the brain [11]. Such communication may enable more accurate entrainment of step timing to music-based auditory cues during temporal RMS [28]. Given the likelihood of similar perception-action pathways invoked by the RA and temporal RMS assessment, it is reasonable to expect that within-group differences in RA and temporal RMS performance are driven by similar constructs, which merits future investigation.

Cognitive deficits in adults with MCI likely masked associations between music relationships or rhythmic proficiency and temporal RMS performance. Individual-specific working memory deficits in the MCI group may explain the more variable temporal RMS performance and may be exacerbated for longer temporal sequences. For example, we previously found that adults with MCI performed longer temporal RMS sequences (6-step duple sequences) less accurately than older adults and that lower temporal RMS performance was associated with worse working memory (i.e., lower scores on the Reverse Corsi Blocks test) [8, 17]. Similarly, lower rhythmic proficiency in adults with MCI, compared to those without MCI, suggests that attentional or motor-cognitive deficits accompanying MCI diagnosis may manifest as a reduced ability to perceive musical cues and entrain motor commands to music [11].

Unlike music relationships, stronger relationships to dance are not indicative of a better ability to accurately perform spatial RMS. Rather, our prior study found that differences in spatial RMS performance are better explained by differences in age-related motor and cognitive function [8]. Therefore, stronger dance relationships do not likely enhance constructs that are beneficial to spatial RMS performance consistently across individuals. For example, the experiences assessed by the DRQ do not require good balance ability or the large joint ranges of motion prescribed by spatial RMS [29]. Prior experience in non-dance activities like gymnastics may, therefore, be a better indicator of an individual's ability to perform spatial RMS [30, 31]. Identifying specific subcomponents of dance relationships or other dance-related experiences that predict the ability to modulate spatial aspects of movement is an interesting future research direction.

Similarly, neither relationships to music or dance, nor rhythmic proficiency are indicative of better spatiotemporal RMS performance. As discussed in the prior paragraph, constructs not evaluated by the MRQ, DRQ, or RA likely impact spatial RMS performance, which constitutes half of the spatiotemporal RMS error used to quantify performance. Further, the constructs assessed by the MRQ and RA do not likely benefit the spatial aspects of RMS performance, as spatial RMS does not require synchronizing motor commands to rhythmic cues [29, 32]. Rather, differences in motor function (e.g., balance) or cognitive function (e.g., set shifting), appear to better predict the ability to perform spatiotemporal RMS [8, 16, 17, 33].

Several factors limit the generalizability and interpretation of our results. Limitations related to our experimental protocol and RMS performance quantification are discussed in [8]. While the OA and MCI group sample sizes in this study were larger than in [8] and [27], still larger sample sizes would improve confidence in our regression results for groups with highly variable RMS performance. Further, our analyses did not adjust for within-group effects of motor or cognitive function, or their interactions with music or dance relationships, on RMS performance [8]. Such an adjustment in future larger-sample studies would improve our understanding of how constructs underlying motor and cognitive function interact with music and dance relationships or rhythmic proficiency to influence the ability to perform RMS.

Additionally, the MRQ, DRQ, and RA represent a preliminary characterization of music relationships, dance relationships, and rhythmic proficiency, respectively. The questionnaire/assessment items encompassed multiple constructs that may impact RMS performance. Computing MRQ, DRQ, and RA composite scores by averaging the scores for all items may mask more nuanced associations between music and dance relationships and RMS performance. Analyzing individual questionnaire items may reveal subcomponents of music and dance relationships that are more strongly associated with RMS performance.

Conclusions

We investigated the relationships between rhythmic movement sequence (RMS) performance and novel assessments of peoples' relationships to music and dance, as well as rhythmic proficiency. The associations of only music relationships and rhythmic proficiency with temporal RMS in young and older adults without, but not with, MCI suggest that cognitive deficits in adults with MCI likely hinder the ability of music relationships or rhythmic proficiency to improve performance on dance-like RMS. These findings contribute to a growing understanding of the factors influencing the ability to accurately perform dance-like movements, which may inform the personalization of dance-based therapies.

Author contributions

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J. Lucas McKay (Conceptualization; Data Curation; Funding Acquisition; Methodology; Software; Supervision; Writing – review & editing)
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Conflict of Interest

The authors have no conflict of interest to report.

Data availability

The data supporting the findings of this study are openly available as Supplemental Material. These data were derived from the following resources available in the public domain: https://www.frontiersin.org/articles/10.3389/fnhum.2023.1040930/full.

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