Investigating the Influence of Groove and Metronome Pitch on Walking Speeds and Variability Using Rhythmic Auditory Stimulation in Healthy Adults

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Neuroscience 3996F & 3997G: Independent Study

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April 8, 2024

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Listening to music enables us to develop a sense of inner rhythm that allows us to conduct a variety of movements. This can involve spontaneously nodding our heads, tapping our feet, or even breaking out in full-body dances (Burger et al., 2018). We can do these movements because we 'feel the beat' of the music (Zuk et al., 2018). A musical beat is the fundamental time interval that we tap into, known as a consistent recurring pulse that can ignite our desire to follow and synchronize with it (Grahn & Rowe, 2013; Leow et al., 2018).

In particular, music and metronome cueing have proven beneficial in improving gait impairments. This method is known as Rhythmic Auditory Stimulation (RAS), where gait-disordered patients like those with Parkinson's Disease (PD) synchronize their footsteps to the beat of different auditory stimuli (Leow et al., 2021). PD patients often demonstrate poverty in movement, as they may experience gait hypokinesia, tremors, rigidity, and unstable posture while walking (Howe et al., 2003; Hausdorff, 2009). In addition, patients with PD have compromised basal ganglia and mesial premotor systems—areas that are crucial in processing beat-based rhythms (Grahn & Brett, 2009; Grahn & Brett, 2007). Literature suggests that RAS effectively enhances walking in individuals by eliciting faster cadence and velocity, longer strides, improved balance, and reduced falls (Leow et al., 2021; Ready et al., 2022; Capato et al., 2020; Howe et al., 2003; Thaut et al., 2019; Wang et al., 2022). Since musical stimuli could be deemed more pleasurable than metronome cues, it is worthwhile to fine-tune musical stimuli selection and continue investigating how beat synchronization in different music pieces influences gait (Leow et al., 2021). Musical cueing is also preferred over metronome cueing as studies have found that music generated faster velocity due to longer stride lengths while metronome cues did not (Wittwer et al., 2013).

Several factors have been discovered to modulate the efficacy of RAS. For example, studies have found that music with a higher familiarity can potentially enhance walking speeds and synchronization accuracy, increase stride length, reduce the number of variable strides, and improve beat salience in both healthy adults and PD individuals (Leow et al., 2015; Park et al., 2021). Furthermore, these studies identified a positive correlation between familiarity and enjoyment, where participants were inclined to experience pleasant arousal responses when listening to music they recognized (Park et al., 2021).

Of all the factors that modulate RAS, we are most interested in investigating the effects of groove in music. Groove is the "pleasurable sensation of wanting to move to music" (Elst et al., 2021). It is a musical experience that induces a desire to move or dance through foot tapping, head nodding, body sways, and more (Madison et al., 2011). On a neuronal level, higher-groove music modulates corticospinal excitability more effectively than low-groove music through the increase of motor-evoked potentials (MEPs), suggesting that the 'groovy-ness' naturally activates the motor system (Stupacher et al., 2013). This is especially true for musicians who have developed stronger auditory-motor connections through consistent music training (Stupacher et al., 2013). fMRI studies have also shown that rhythm perception activates various motor regions of the brain, including the supplementary motor area (SMA) and basal ganglia, regardless of whether one is actively moving (Chen et al., 2008; Grahn & Brett, 2007). Additionally, groove does not only pertain to one's movement but also generates positive emotions and pleasurable sensations, even in the presence of rhythmically complex stimuli involving the use of syncopation (Elst et al., 2021; Witek et al., 2014).

Previous literature has shown the effects of higher groove and beat involvement on gait, notably generating faster strides and less variability while walking (Leow et al., 2021; Ready et al., 2019; Leow et al., 2014). Previous studies noted that RAS slowed participants down in general, but that music with a higher groove elicited faster and longer strides than low-groove music (Ready et al., 2019). Leow et al. (2021) also showed that high-groove music generated faster steps regardless of whether individuals were told to synchronize to the beat or not. These researchers tested both younger and older individuals with varying levels of beat perception ability. They found that pronouncing the beat with a metronome increased stride velocity when walking to low-groove music. Embedding metronomes on low-groove music seemed to bring a larger effect than high-groove music, as participants may have found synchronizing less difficult, resulting in lower gait variability (Leow et al., 2021). On the contrary, high-groove may have already contained a high beat salience, hence embedding a metronome did not significantly alter most gait parameters, as this addition could have been deemed redundant (Leow et al., 2021).

The current study also investigates a possible interaction between one's ability to perceive a musical beat and synchronization instructions. Beat perception ability impacts how one walks to musical stimuli compared to silence. When walking to music, poor-beat perceivers showed slower stride lengths and velocities compared to their baseline walks, while good-beat perceivers did not (Ready et al., 2019). It is thought that poor-beat perceivers find it difficult to walk to the music because they need to dedicate more attention to identifying and recognizing the beat (Ready et al., 2019). However, instructions do not always involve telling participants to synchronize to the beat. They could also be instructed to free-walk (i.e., be instructed to walk in a way that feels most natural to them). Previous studies found that most individuals who were asked to free-walk did not attempt to align their footsteps to the beat, meaning that the instruction to synchronize could ensure that certain individuals (e.g., gait-disordered patients) are synchronizing their footsteps (Leow et al., 2018). The effect of these instructions on healthy younger adults was visualized in walking. It was found that good-beat perceivers had a more accurate cadence and longer stride lengths when told to synchronize (Ready et al., 2019). On the contrary, poor beat perceivers exhibited improved balance-related parameters when told to free-walk; since poor beat perceivers struggle to synchronize to the beat on purpose, asking them to walk naturally may, instead, improve their gait parameters (Ready et al., 2019).

Since most researchers (e.g., Leow et al. 2021) examined the effects of groove in gait with a relatively high-pitched metronome, it is worthwhile to investigate whether the sound frequency of a metronome would exhibit any effect on gait performance as well. Literature suggests there is a low-tone advantage to rhythm processing, where bass sounds play privileged roles in beat salience entrainment (Lenc et al., 2023). It has been shown that participants were more active and exhibited better tempo synchronization (i.e., dance movement) as the sound pressure level of a bass drum increased (Van Dyck et al., 2013). Another study found similar results when analyzing the movements of individuals listening to musical stimuli of popular genres; people's local movement, which involves speed, acceleration, and jerk of different body parts, increased when a clear beat was presented in the low-frequency range, whereas a less clear beat within this range prompted participants to wander more, as if they were trying to localize the beat (Burger et al., 2010). Another study recorded the neural activity of infants using electroencephalography (EEG) to determine if the low-tone benefit is simply due to long-term exposure to music (Lenc et al., 2023). The researchers discovered that there is selective enhancement during meter frequencies, specifically increased neural activity when the rhythm is presented in low-pitch sounds. This suggested that the low-tone advantage may be present during prenatal development, as well as activation of the vestibular system through the mother's movement (Lenc et al., 2023).

Our Study

According to our knowledge, the current literature has not connected the differences in metronome pitch to gait. Since lower beat pitch correlates to an increase in groove (Cameron et al., 2022), it is worthwhile to investigate whether the comparison of higher and lower metronome pitches elicits improvements in gait. Additionally, it is crucial to investigate whether higher or lower beat salience changes people's perception of groove.

The current study will investigate both of these aspects by having healthy individuals walk along to high- and low-groove music accompanied by high- and low-pitched metronomes. As high-groove music generally contains a higher beat salience compared to low-groove music, we predict that embedding metronomes in high-groove music will not lead to a significant difference in gait performance. Alternatively, we predict that adding a metronome to low-groove music will enhance the beat salience in such a way that significantly improves gait performance. We specifically predict that this improvement will be significantly larger when the metronome is of lower pitch. If embedding a low-pitched metronome further increases the beat salience of high-groove music as well, then we will be able to conclude that there is a low-tone advantage in rhythm processing and that bass sounds likely to improve gait in both high- and low-groove music.

In addition, we will assess participants' beat perception ability and instruct each of them to either free-walk or synchronize, as previous literature has shown these factors heavily influence one's ability and tendency to spontaneously synchronize to musical stimuli (Leow et al., 2014; Leow et al., 2018; Ready et al., 2019). Based on past studies, the current study predicts that good-beat perceivers will synchronize to the beat more effectively when asked to synchronize compared to "free-walk", whereas poor-beat perceivers will synchronize to the beat more effectively when asked to "free-walk".

We hypothesize that high-groove music will elicit faster gait speeds and longer stride lengths than low-groove music and that this effect will be more pronounced when participants are instructed to synchronize to the beat of the music (Leow et al., 2021; Ready et al., 2022). We also hypothesize that participants will elicit faster and less variable gait speeds in songs with low-pitched metronome beats, given that low-frequency sounds are related to a greater amount of synchronization in spontaneous movement (Lenc et al., 2023; Lenc et al., 2018).

Method

Participants

A total of 40 healthy younger adults (ages 18 to 40) and 33 healthy older adults (ages 50 or above) were included in the study, as part of a recruitment sample of 44 healthy younger adults and 36 healthy older adults. Participants were screened to ensure all eligibility criteria had been met: age eligibility, no neurological disorders, and no vision or hearing disorders. Participants did not undergo any cognitive screening tests during the experiment. Four younger adults were excluded from the study due to insufficient datasets and three older adults were excluded due to technological issues. Participants were either recruited through community posters in London, Ontario or via the Psychology SONA pool at Western University. Participants were compensated in the form of cash or SONA credit, respectively. Written consent was obtained and documented per the guidelines of the Nonmedical Research Ethics Board of Western University.

Research Design

Our study contained a total of five independent variables—groove, beat salience, beat perception ability, synchronization instructions, and age. Groove and beat salience were within-subject factors, with one's perceived groove being categorized as high or low and beat salience being categorized by embedding high-pitched or low-pitched metronome beats into stimuli. Beat perception ability, synchronization instructions, and age were within-subject factors. Participants were categorized as either good or poor beat perceivers, told to "free-walk" or synchronize to the beat of music, and were categorized as either younger or older adults, respectively. 2 x 2 x 2 x 2 x 2 mixed-measures ANOVAs were run with the above factors on three spatiotemporal gait parameters—cadence, stride length, and stride velocity. These factors were treated as dependent variables of the study.

Stride length (in centimetres) refers to the anterior-posterior distance from the moment one foot comes in contact with the ground to the moment the next ipsilateral foot comes in contact with the ground (Leow et al., 2021). Stride velocity (in *centimetres/second*) refers to the stride length divided by stride time (in *seconds*); if stride length increases (i.e., taking longer steps) or stride time decreases (i.e., taking more steps within a certain amount of time), the stride velocity would increase (Leow et al., 2021). Cadence in (in *steps/min*) refers to an important ambulatory movement pattern that indicates how accurately one is walking to the beat. Alongside stride length, this variable portrays the speed of ambulation (Tudor-Locke et al., 2020).

Procedure

Baseline Gait Measurement

Participants first walked on a built-in 16-foot Protokinetics Zeno® pressure sensor walkway gait mat (579 x 90.2 x 90.2 centimetres) in silence for six lengths as a baseline trial. They were instructed to walk in a manner similar to their natural everyday walk. The gait mat contained active sensors spanning 488 centimetres by 61 centimetres that allowed us to detect and measure gait parameters. To process and visualize participant data, ProtoKinetics Movement Analysis Software (PKMAS) was used. This program was designed to accompany the walkway mat, allowing us to sample footfall data at a rate of 120 Hz with a spatial resolution of 1.27 centimetres. Once the baseline trial was processed, the cadence value (in *steps*/*min*) was recorded to the nearest integer.

Generating & Selecting Stimuli

Stimuli consisted of ten different songs chosen from a previous database of musical studies and both high-pitched and low-pitched metronome beats. Ableton® was used to incorporate both high-pitched (cowbell-like) and low-pitched metronome (bass drum-like) into the songs individually, aligning them to the beat of the music. As a result, a total of 20 musical stimuli were generated, where each song had a low- and high-metronome version. Files of stimuli at different tempos were generated using Audacity® (http://audacity.sourceforge.net), where we adjusted songs and metronome beats from 110 bpm to 90-140 bpm. Each clip also was normalized to be the same volume as one another. Stimuli were played over wireless headphones (Sennheiser® HDR 160) for all components of the study.

Once a participant's baseline cadence value had been recorded, a file with the 20 musical stimuli was generated at a tempo that was 10 percent faster than the cadence. Participants listened to and rated the songs (see below, "Rating Task"). Songs were first grouped by metronome type ("high metronome" and "low metronome"), then each group was split into two, with the five higher groove ratings values considered "high groove" whereas the five lower groove ratings values considered "low groove." In both metronome groups, the song with the highest beat salience rating in the high-groove group and the song with the lowest beat salience of the low-groove group were removed, in order to equalize the level of beat salience across songs. As a result, there was a total of 16 songs, as well as eight metronome clips, totalling 24 stimuli files (Table 1). The metronome clips included high and low metronome stimuli in the absence of songs (Table 1).

Table 1

Participant Stimuli Conditions and Descriptions

Conditions	Descriptions

HGHM (4 trials)	Songs that consist of **high** groove ratings and had a **high**-pitched of metronome
HGLM (4 trials)	Songs that consist of **high** groove ratings and had a **low**-pitched metronome
LGHM (4 trials)	Songs that consist of **low** groove ratings and had a **high**-pitched metronome
LGLM (4 trials)	Songs that consist of **low** groove ratings and had a **low**-pitched metronome
HMET (4 trials)	High-pitched metronome only
LMET (4 trials)	Low-pitched metronome only

Note. HGHM = high-groove high-pitched metronome; HGLM = high-groove low-pitched metronome; LGHM = low-groove high-pitched metronome; LGLM = low-groove low-pitched metronome; HMET = high-pitched metronome only; LMET = low-pitched metronome only.

Beat Alignment Test (BAT)

To examine participants' beat perception ability, individuals completed the Beat Alignment Test (BAT) from the Goldsmiths Music Sophistication Index v1.0 (Müllensiefen et al., 2012). The BAT consisted of two parts: a beat production and beat perception task. The beat production task involved music clips of different tempi to assess participants' ability to tap along with the beat of the music. The beat perception task asked participants to recognize whether the metronome beeping embedded in music clips aligns correctly with the beat. There were 13 beat production trials with one practice trial and 17 beat perception trials with three practice trials. The test was administered on E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA) and the data was analyzed using the E-Merge application, which combined participants' E-Studio files into one spreadsheet. The 17 beat perception trials revealed participants' answers on whether the beeping was in time of the beat, indicating "y" for yes and "n" for no. Medians amongst older and younger adults were computed and those who fell above the median were considered "good beat-perceivers" while those below the median were "poor beat-perceivers."

Song Ratings

After the file with 20 musical stimuli was created, participants rated each stimulus under four categories—familiarity, groove, enjoyment, and beat salience, using a Likert scale of 1 to 100. The questions were: (1) How familiar are you with this piece of music? (2) How much does this piece of music make you want to move to it? (3) How much do you enjoy listening to this piece of music? (4) How strong is the beat in this piece of music? Both the high-metronome and low-metronome versions of each song were played to evaluate differences in ratings of the same songs embedded in different metronome pitches, which could potentially alter one's perception of groove of the piece itself (Leow et al., 2021). Each stimulus was played for approximately 30 seconds and participants were allowed to produce ratings during and after each played stimuli.

Cued Gait Trials

Similar to the baseline gait measurement, each trial required participants to walk on the walkway for six lengths. The tempo of music and metronome beats participants walked to were adjusted to 10 percent faster than their respective baseline cadences. For example, if the baseline cadence was 103 *steps/min*, the stimuli were all at 113 bpm. Half of the participants were instructed to walk in a way that feels most natural to them (i.e., free-walk), while the rest were instructed to try their best to synchronize their footsteps to the beat of the music and metronomes. All participants included in the analyses completed 24 trials (see above, "Creating & Selecting Stimuli"). 16 of 24 trials involved music pieces that were categorized to either high or low grooves according to song ratings, embedded with either high- or low-pitched metronome. The remaining 8 trials consisted of four high-pitched metronome and four low-pitched metronome stimuli. To randomize conditions within these 24 trials, a Latin square design was implemented to ensure all order combinations were equally represented. Participants were assigned to one of three order conditions listed in Figure 1.

Figure 1

Latin Square Design for Participant Walking Trials

Trial No.	Order 1	Order 2	Order 3
1	LGLM	LGLM	LGHM
2	LGLM	LMET	LGHM
3	HGHM	HMET	LGLM
4	LMET	HGHM	LMET
5	LGHM	HGHM	HGHM
6	HGHM	LMET	HGHM
7	HGLM	LMET	LGLM
8	LGHM	LGLM	HMET
9	HMET	HMET	HGHM
10	HMET	HGLM	LGHM
11	HGLM	LGLM	LMET
12	HMET	LGHM	HMET
13	LMET	LGLM	LGLM
14	HGLM	HGLM	LGLM
15	LGLM	HGLM	HGLM
16	HGHM	HGHM	LGHM
17	HGLM	HMET	HGLM
18	LMET	HMET	HGLM
19	LGHM	LGHM	HMET
20	HMET	LGHM	LMET
21	LGHM	HGLM	LMET
22	HGHM	LMET	HGHM
23	LGLM	HGHM	HMET
24	LMET	LGHM	HGLM

Note. HGHM = high-groove high-pitched metronome; HGLM = high-groove low-pitched metronome; LGHM = low-groove high-pitched metronome; LGLM = low-groove low-pitched metronome; HMET = high-pitched metronome only; LMET = low-pitched metronome only.

Data Analyses

The stimuli files for rating and walking tasks were generated by MATLAB2021 and the walking tasks were run in conjunction with MATLAB2015b and PKMAS, where MATLAB2015b detected the “Start Walk” signal from PKMAS for every trial and started playing the stimuli for participants to walk to. After each experiment, the 24 cued walks were processed on PKMAS and each trial generated a text file containing their walking cadence, stride velocity, stride length, stride width, stride time, and more gait parameters. Cadence, stride velocity and stride length were analyzed using RStudio 2022.12.0+353. Raw walking data was also normalized to account for individual differences:

$$Normalized\ score\ = \frac{(cued\ parameter - baseline\ parameter)}{baseline\ parameter}.$$

Results

Participant Analysis

42 younger adults (ages 18 to 40) and 31 older adults (ages 50 or above) participated in this study. We tested the impact of perceived groove, beat salience, beat perception ability, synchronization instructions, and age on gait patterns (see “Research Design” in Methods).

Demographic data is presented by subgroup in Table 1. There were notably more younger adults than older adults, but the number of participants across the free-walking and synchronized groups was relatively equal. In terms of age, younger adults had a much smaller deviation than older adults, suggesting that the younger adult cohort was more homogenous than the older adult cohort. Most participants in this study were female (65.75%), especially in the older adult cohort. The mean baseline cadence of older adults was higher than that of younger adults, but similar standard deviations showed variability in these baseline values were variable between participants in all groups.

Table 2

Demographic data categorized by age and synchronization instructions condition

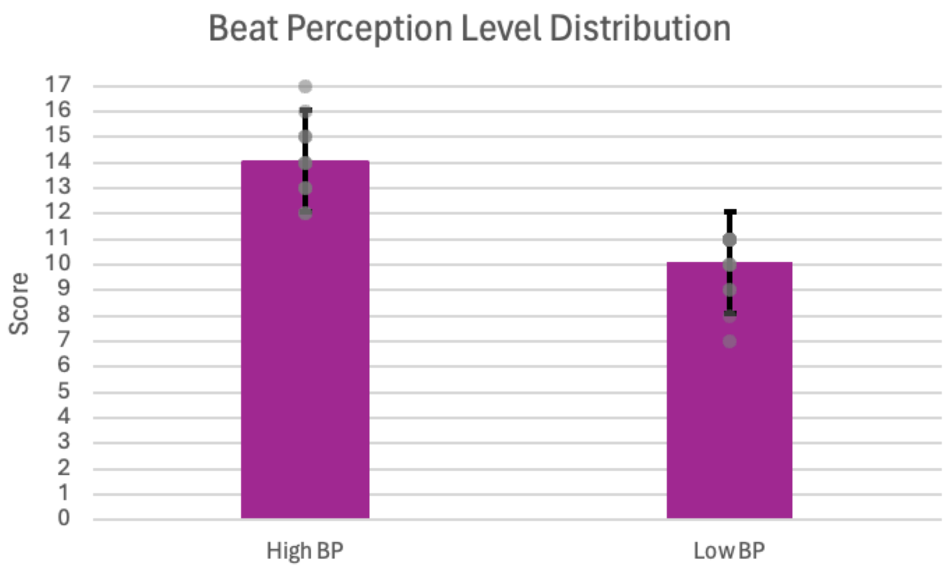
	Older		**Younger**	
	Free-walk (n=16)	**Synchronize (n=15)**	**Free-walk (n=21)**	**Synchronize (n=21)**
Beat Perception (% correct)				
Mean (SD)	69.49 (13.62)	69.41 (11.81)	72.55 (15.04)	68.07 (15.96)
Age				
Mean (SD)	61.00 (8.36)	66.13 (9.17)	20.24 (3.06)	18.81 (1.21)
Gender				
Female	12 (75%)	11 (73.33%)	13 (61.90%)	12 (57.14%)
Male	4 (25%)	4 (26.67%)	8 (38.10%)	9 (42.86%)
Baseline Cadence				
Mean (SD)	111.25 (8.23)	112.67 (6.74)	105.38 (9.14)	105.43 (7.12)

Beat Perception Level

There is variability in how well participants may recognize and tap to the beat. Categorizing participants into high and low-beat perceivers allows us to account for these differences. One's beat perception level was determined by their performance on the 17 beat perception trials during the BAT (see "Beat Alignment Test" in Methods). Referencing previous literature, participants with a score lower than 65% (≤ 11 out of 17) were classified as low-beat perceivers, while those with a score higher than 70% (≥ 12 out of 17) were classified as high-beat perceivers (Ready et al., 2022; Roberts et al., 2021). Figure 1 shows the distribution of beat perception scores, indicating the average scores of high-beat perceivers (M = 14.06) and low-beat perceivers (M = 10.10). The highest score achieved was 17 (100%) and the lowest score achieved was 7 (41.18%).

Figure 2

Mean distribution of beat perception scores



Cadence

A person's cadence is defined as the rate of their walking, with the units of "steps per minute." Cadence can vary amongst individuals but is usually within the range of 100 to 130 steps/min, which is characterized as walking at moderate intensity (Slaght et al., 2017). Baseline cadences (i.e., normal walking speeds without musical stimuli) were used to determine stimuli meters. Songs and metronome beats participants walked to were set to be 10% faster than baseline. The cadences at which the participants walked for each song or beat trial were recorded by PKMAS. Analyzing cadence changes compared to baseline allowed us to deduce how accurately one matched their footsteps to the beats of the music or metronome. The closer the change was to the +10% cadence value, the more accurate one's cadence was to the adjusted tempo of the music or metronome.

Figure 3 shows the mean percent change in cadence of all participant walk trials, categorized by groove, beat salience, beat perception, instructions condition, and age. A significant main effect of groove ($F_{1,65} = 19.44$, $p < .001$) was observed, suggesting that participants were walking more accurately to the beat in high-groove music [$M = 6.05\%$, $SE = .59\%$] compared to low-groove music [$M = 4.90\%$, $SE = .58\%$]. A significant main effect of instructions ($F_{1,65} = 26.49$, $p < .001$) was also observed, where the mean percent change of participants asked to synchronize to the beat [$M = 8.42\%$, $SE = .82\%$] was significantly higher than the change of those asked to walk freely [$M = 2.54\%$, $SE = .80\%$]. There were no significant main effects of beat salience ($F_{1,65} = .52$, $p = .47$), beat perception level ($F_{1,65} = 2.46$, $p = .12$), or age ($F_{1,65} = .59$, $p = .45$) observed. This suggested that there were no significant effects between the change of cadence in high-pitched [$M = 5.44\%$, $SE = .57\%$] and low-pitched [$M = 5.52\%$, $SE = .58\%$] metronomes in music, between high-beat [$M = 6.38\%$, $SE = .85\%$] and low-beat perceivers [$M = 4.58\%$, $SE = .76\%$], and between younger [$M = 5.92\%$, $SE = .74\%$] and older adults [$M = 5.04\%$, $SE = .87\%$]. To better visualize main effects, Figure 4 shows the mean percent change categorized by groove, beat salience, and instructions conditions. It is evident that participants asked to synchronize exhibited a more accurate cadence (closer to +10% baseline cadence) than participants asked to free-walk. Across both instruction conditions, it is also evident that higher-groove songs have a slightly higher cadence than lower-groove ones. In terms of beat salience, the "High Met" and "Low

Met" columns are all relatively similar to one another, hence there seems to be no effect on whether the inclusion of a higher- or lower-pitched metronome makes one walk more accurately to the beat.

Figure 3

Mean percent change in walking cadence categorized by all independent variables

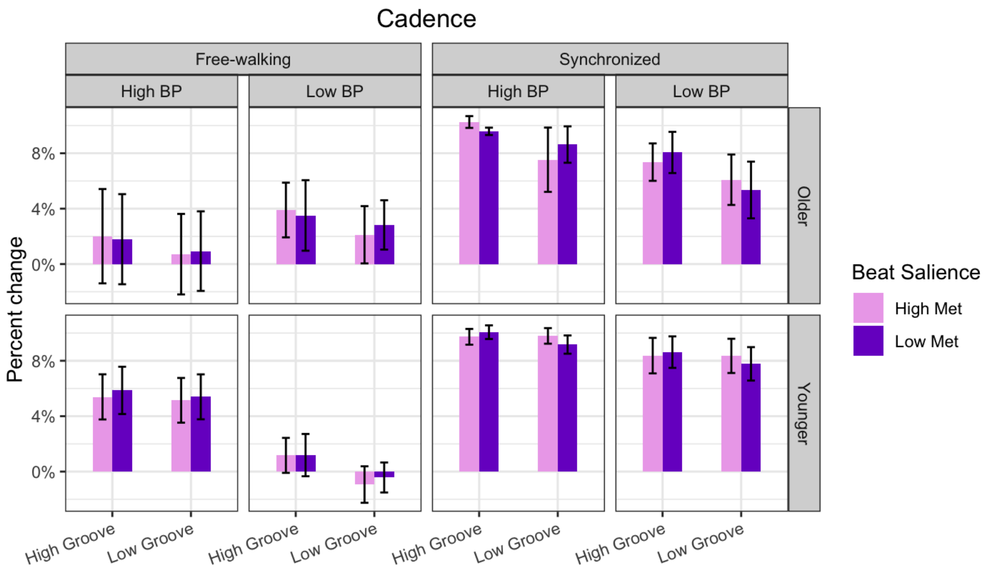
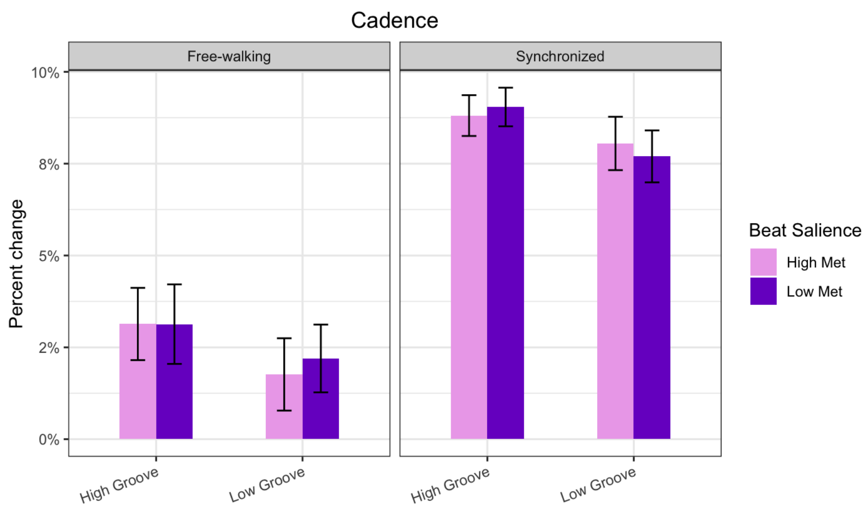


Figure 4

Mean percent change in walking cadence categorized by groove, beat salience, and instructions condition



Stride Length

Stride length is the anterior-posterior distance from the moment one foot comes in contact with the ground to the moment the next ipsilateral foot comes in contact (Leow et al., 2021). Calculated in centimetres, stride length serves as a fundamental metric in understanding the efficiency, stability, and overall quality of locomotion. Assessing stride length provides insights into an individual's gait pattern and speed. This can allow researchers to identify potential age differences, such as slowed gait in older adults, and gait abnormalities in Parkinson's disease (Zanardi et al., 2021; Ferrandez et al., 1996). Analyzing stride length also allows us to understand gait dynamics by examining its interplay with other parameters like stride velocity. Each song or beat trial on PKMAS produces a mean value of all stride lengths for both feet and this value has been converted to a normalized score (see "Data Analyses" in Methods). Results show the change in mean scores compared to the baseline stride length mean, allowing us to compare between conditions.

Figure 5 shows the mean percent change in stride length of all participant walk trials, categorized by groove, beat salience, beat perception, instructions condition, and age. Significant main effects of groove ($F_{1,65}$ = 15.00, p < .001) and beat salience ($F_{1,65}$ = 5.00, p = .029) were recorded. Moreover, an interaction between groove and beat salience ($F_{1,65}$ = 9.89, p = .0025) was present. As illustrated in Figure 6, there were no significant differences when high-pitched [M = .20%, SE = .65%] or low-pitched metronomes [M = .097%, SE = .60%] were embedded in low-groove music, but in high-groove music, the inclusion of low-pitched metronome [M = 1.60%, SE = .76%] elicited longer stride lengths compared to high-pitched metronome [M = .65%, SE = .72%]. A significant main effect of beat perception level ($F_{1,65}$ = 4.75, p = .033) was also found, where high-beat perceivers [M = 2.08%, SE = .99%] took significantly longer strides than low-beat perceivers [M = -.80%, SE = .88%]. As illustrated in Figure 7, high-beat perceivers lengthened their strides while low-beat perceivers shortened their strides compared to baseline. Although there were no significant main effects of instructions and age, a significant interaction was found between the two variables ($F_{1,65}$ = 4.28, p = .043). As illustrated in Figure 8, older adults shortened their strides when asked to synchronize [M = -2.06%, SE = 1.46%] compared to free-walk [M = 1.27%, SE = 1.39%], while younger adults did the opposite (lengthened their strides when asked to synchronize [M = 2.73%, SE = 1.21%] compared to free-walk [M = .60%, SE = 1.21%]). It is also notable that the group of older adults instructed to synchronize to the beat were taking shorter strides than their initial baseline stride length.

Figure 5

Mean percent change in stride length categorized by all independent variables

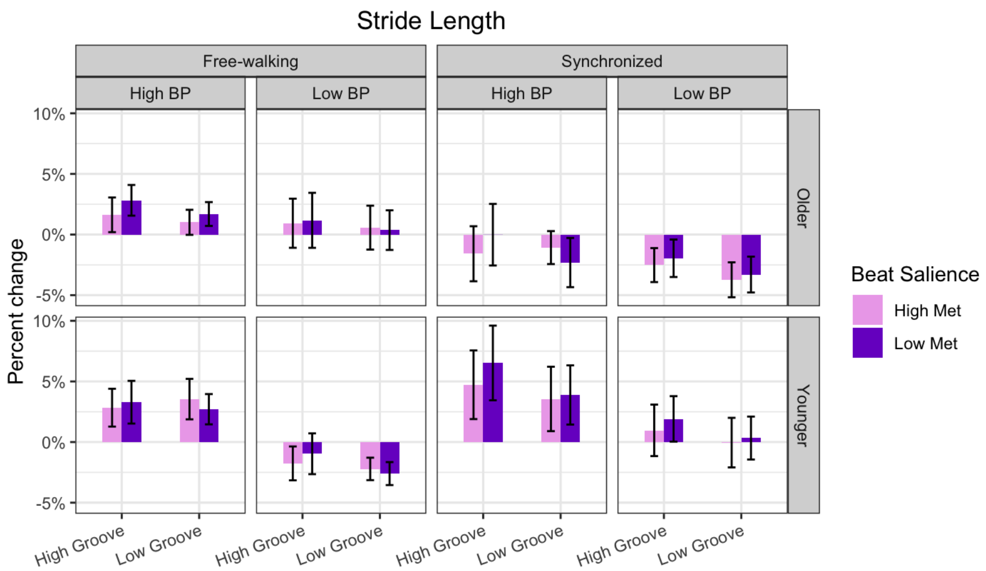


Figure 6

Mean percent change in stride length categorized by groove and beat salience

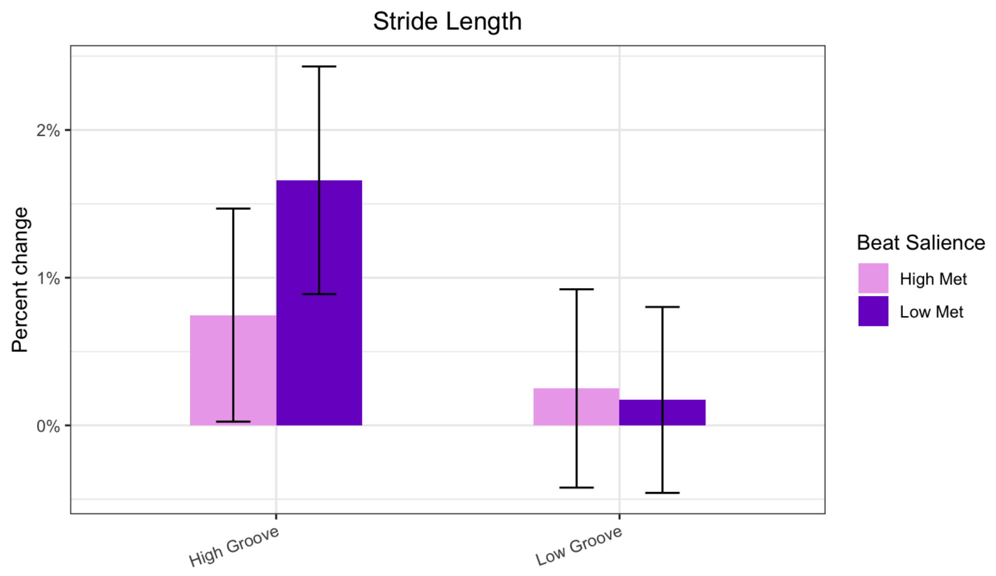


Figure 7

Mean percent change in stride length categorized by groove, beat salience, and beat perception

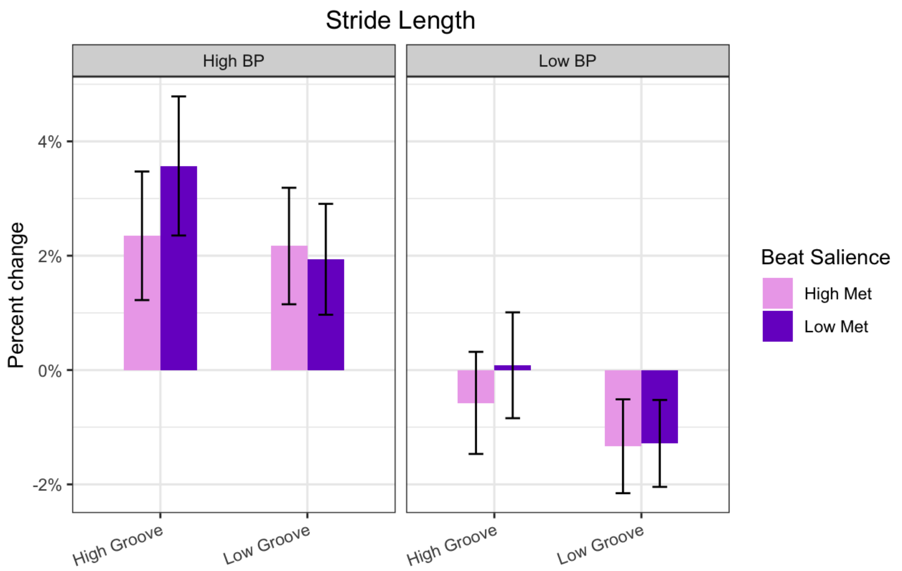
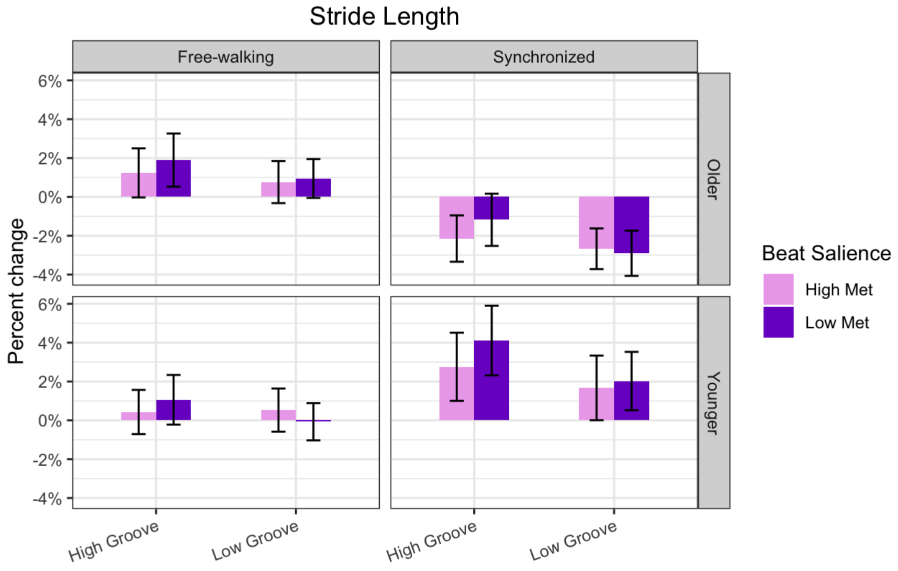


Figure 8

Mean percent change in stride length categorized by groove, beat salience, instructions condition, and age



Stride Velocity

Stride velocity refers to how fast one is walking, defined as the stride length divided by stride time. As a result, if one is taking longer strides and spending less time between steps, stride velocity increases. This measure serves as a crucial outcome in evaluating how effective different interventions are in improving walking ability and restoring functional independence. By measuring the speed at which an individual covers a certain distance within a single stride, researchers can gain valuable insights into the stability of their gait pattern, especially concerning sudden speed changes (Park and Park, 2023). PKMAS records the velocity of each step and provides a mean value of all stride velocities. Similar to stride length, these scores are normalized and the results of each trial are compared to the baseline mean.

Figure 9 shows the mean percent change in stride velocity of all participant walk trials, categorized by groove, beat salience, beat perception, instructions condition, and age. Significant main effects of groove ($F_{1,65} = 25.66$, $p < .001$) and beat salience ($F_{1,65} = 7.35$, $p = .0086$) were found, and a significant interaction between groove and beat salience ($F_{1,65} = 4.01$, $p = .049$) was also present. Figure 10 indicates that higher-groove music [M = 7.16%, SE = 1.06%] elicited significantly higher stride velocity than lower-groove music [M = 4.99%, SE = .92%], regardless of which metronome was included. In the low-groove category, there were no differences in velocity change between songs with high-pitched [*M* = 4.96%, *SE* = .96%] and low-pitched metronomes [*M* = 5.03%, *SE* = .91%]. In the high-groove category, songs with a lower metronome [*M* = 7.72%, *SE* = 1.11%] elicited a slightly higher stride velocity than songs with a higher metronome [*M* = 6.60%, *SE* = 1.03%]. A significant main effect of beat perception ($F_{1,65} = 6.27$, $p = .015$) suggests that participants categorized as high-beat perceivers [*M* = 8.49%, *SE* = 1.44%] had a significantly higher stride velocity than low-beat perceivers [*M* = 3.66%, *SE* = 1.28%], regardless of what songs they were walking to (see Figure 11). Similarly, a significant main effect of synchronization instructions ($F_{1,65} = 7.22$, $p = .0091$) illustrates that participants instructed to synchronize to the beat [*M* = 8.67%, *SE* = 1.38%] elicited significantly faster velocities than those instructed to walk freely [*M* = 3.48%, *SE* = 1.35%], regardless of song choice (see Figure 12).

Figure 9

Mean percent change in stride velocity categorized by all independent variables

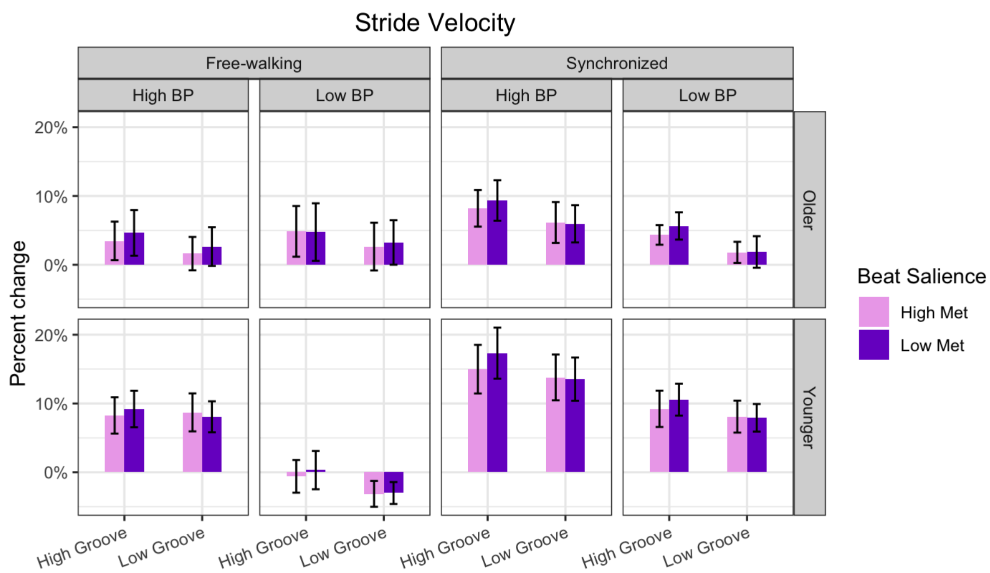


Figure 10

Mean percent change in stride velocity categorized by groove and beat salience

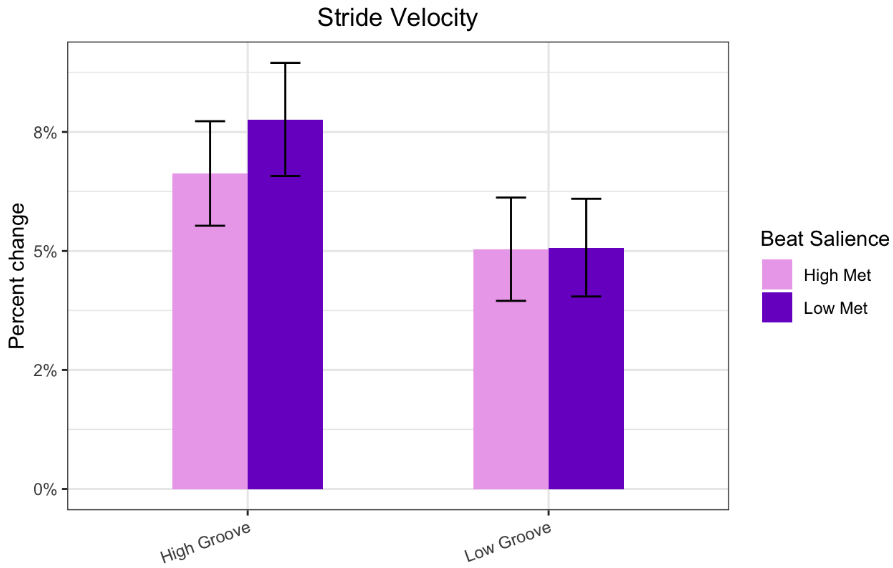


Figure 11

Mean percent change in stride velocity categorized by groove, beat salience, and beat perception level

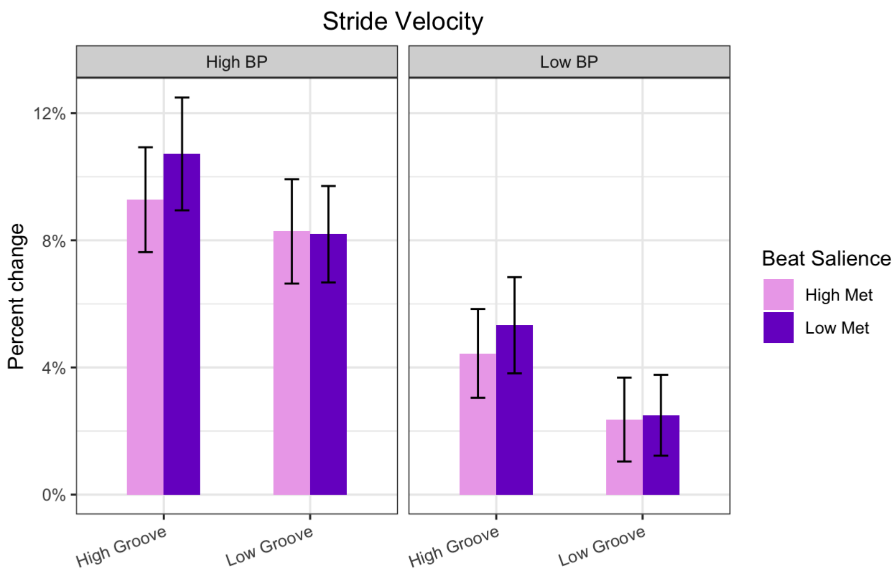
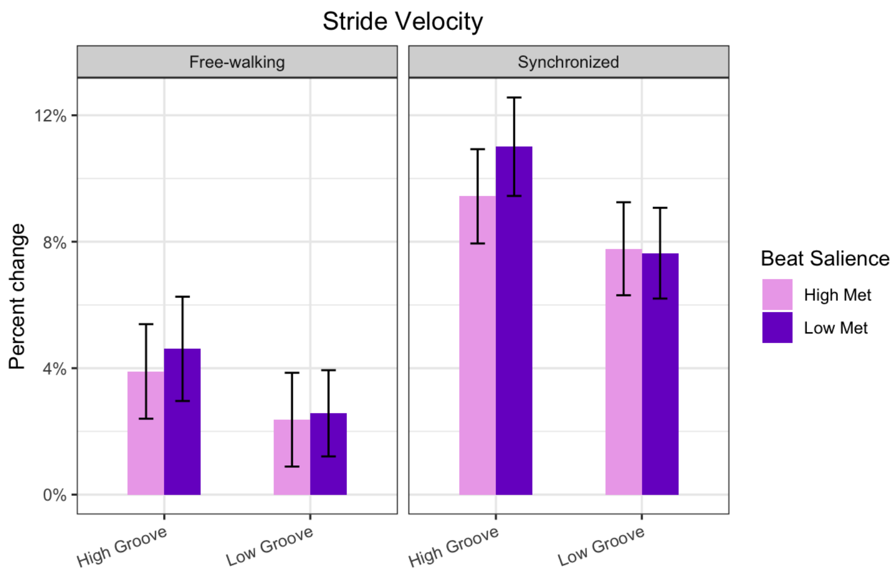


Figure 12

Mean percent change in stride velocity categorized by groove, beat salience, and synchronization instructions



Discussion

In the present study, we examined how one's perceived groove and beat salience impact the way one walks, potentially leading to improvements in different gait parameters. We have also considered differences in synchronization demands and beat perception levels, as these factors may influence how well one naturally walks and responds to music. Overall, several gait outcomes were influenced by groove and beat salience in both healthy younger and older adults.

Higher-groove music improves gait parameters

High-groove music consistently improved various gait parameters, including walking cadence, stride length, and stride velocity, notably eliciting longer and faster strides compared to low-groove music. These findings support our hypothesis and agree with previous literature about groove effects on gait (Ready et al., 2022; Leow et al., 2021). Groove effects could be explained by various positive characteristics, where high-groove music is considered more pleasurable and rewarding than low-groove music, encouraging movement vigour (Leow et al., 2021). It is also believed that high-groove music stimulates arousal in the central and peripheral nervous system, activating the locus coeruleus to induce the release of norepinephrine (Bowling et al., 2019).

Instructions to synchronize may lengthen and shorten strides

An interesting discovery we found was a significant interaction between synchronization instructions and age. Previous studies have mentioned that RAS, which involves telling individuals to walk to the beat, generally slowed participants down through the shortening of strides (Ready et al., 2019). However, according to our results, younger adults notably lengthened their strides while older adults shortened their strides when they were told to synchronize. This supports the idea that the effect of RAS on stride length could be mixed, as some studies argue auditory cues increase stride length whereas others suggest cues faster than baseline could negatively impact stride length (Wu et al., 2024). Coincidentally, a study that compared younger and older adults also noticed when older adults tried to maintain the same velocity in walking, they were taking more frequent but shorter steps per minute (Ready et al., 2022). Therefore, we suggest that synchronizing to the beat helps us walk longer and faster at relatively younger ages. However, as we age, we shorten our steps to keep up with the beat.

The low-beat advantage in high-groove music

Previous literature has shown that embedding metronome pulses in music results in improved speed, stride length, and cadence, and such an intervention can be effective in gait-disordered patients, such as Parkinson’s (Hayashi et al., 2006; McIntosh et al., 1997; Thaut et al., 1996). While high-groove music is already considered beat-salient, gait studies have also found that embedding metronomes into low-groove music helps enhance beat salience, creating the same effect of high-groove music on its own (Leow et al., 2021). To take a step further, we embedded the same songs with a high-pitched and a low-pitched metronome to visualize the potential effects of metronome sound frequency on gait performance. We hypothesized that there would be faster and longer strides in songs with a low-pitched metronome compared to those with a high-pitched metronome due to previous literature on the advantage of bass sounds and low-frequency beats (Lenc et al., 2023; Burger et al., 2018). Indeed, we were able to find significant effects of beat salience, where the low-pitched metronome songs elicited longer lengths and faster velocity than the high-pitched metronome songs, agreeing with our hypothesis. However, this effect was only seen in high-groove music. As a result, we are uncertain whether adding a low-pitched metronome in high-groove music actually emphasizes beat salience, given that there were no effects in low-groove music. Since there were also no significant effects of a high-pitched metronome on high-groove music, we postulate that the low-metronome effects may just be due to the low beats being more congruent with the experience of walking to high-groove music, rather than actually enhancing beat salience. To visualize a clearer beat salience effect, future studies can consider comparing these low-pitched metronomes (e.g. bass drum beats) with the songs themselves (without embedding any metronome). Suppose effects of beat salience are seen across both high- and low-groove songs (i.e., higher stride length and velocity in metronome-added songs than songs alone). In that case, we can conclude there is a low-beat advantage on gait and adding low-frequency beats to music could potentially act as an effective intervention in RAS.

Interaction between beat perception and instructions

The inclusion of beat perception and synchronization demands as independent variables was important, as seen from their individual effects on temporal gait outcomes like stride length and stride velocity. Participants with a weaker beat perception ability exhibited slower and shorter gait than those with a stronger ability. This was evident from their smaller increase in stride velocity and decrease in stride length compared to baseline. Since high-beat perceivers may find it easier to synchronize to the beat than low-beat perceivers, they elicited faster gait and lengthened their strides (Leow et al., 2014).

However, the dynamic interplay between these two variables was not supported, as we were unable to visualize an interaction between beat perception and synchronization instructions in any of the outcomes. Previous literature found that low-beat perceivers' ability to match tempo was overall unaffected by these instructions (Ready et al., 2019). In contrast, high-beat perceivers increased their step rate when asked to synchronize and slowed down when asked to walk freely (Ready et al., 2019). We predicted that high-beat perceivers would synchronize more effectively when instructed to synchronize while low-beat perceivers would synchronize more effectively when instructed to free-walk, as we postulated that low-beat perceivers would struggle when told to synchronize and could perform better when not intentionally trying to match their footsteps to the beat. Contrary to our prediction, both groups had a much higher cadence and stride velocity when asked to synchronize compared to free-walking, meaning that both high- and low-beat perceivers were walking faster and more accurately to the beat when we requested them to synchronize. This could have been due to an overestimation of how difficult we thought synchronizing was for low-beat perceivers, as they were also able to match effectively when intentionally walking to the beat. Since our results suggest instructions to synchronize improve gait speed and accuracy in all individuals, these synchronization demands are crucial to include in RAS.

This study comes with some limitations. Sex differences were not considered, as seen from the unequal distribution between males and females (see "Participant Analysis" in Results). The implementation of synchronization instructions may also be unclear since participants assigned to free-walk were only instructed to "walk in a way that feels most natural to them." Feedback from participants after experiments showed that people may interpret this statement as researchers intentionally hinting them not to follow the beat on purpose, or testing them to see if they can walk to the beat without being told. These interpretations may potentially confound results given that participants may not be walking in their most natural state. Another limitation of instructions is it being a between-subject factor, potentially introducing more individual variability into the data. Future studies can explore a within-subjects design, where the same participants were told to synchronize in one session and free-walk in the other. Lastly, experiments were done in an in-lab setting where participants were required to make a turn every time they crossed the gait mat, a procedure that usually does not occur in public settings.

Overall, this study contributes to an established group of literature that found the effects of groove on gait, confirming that higher-groove music can improve spatiotemporal parameters and can be treated as an optimal stimulus in gait rehabilitation for gait-disordered patients to increase and lengthen their strides (Leow et al., 2021). This study also agrees that beat perception levels and synchronization demands should be accounted for in RAS. Since we found that telling participants to synchronize improves gait in both high- and low-beat perceivers, we believe walking with RAS does not increase cognitive load and these synchronization demands should be incorporated into music and walking therapies (Ready et al., 2019). Although some beat salience effects were seen, more work is required to prove the effects of songs with low beats in walking.

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