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RESEARCH ARTICLE

How groove in music affects gait

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Abstract

Rhythmic auditory stimulation (RAS) is a gait intervention in which gait-disordered patients synchronise footsteps to music or metronome cues. Musical 'groove', the tendency of music to induce movement, has previously been shown to be associated with faster gait, however, *why* groove affects gait remains unclear. One mechanism by which groove may affect gait is that of beat salience: music that is higher in groove has more salient musical beats, and higher beat salience might reduce the cognitive demands of perceiving the beat and synchronizing footsteps to it. If groove's effects on gait are driven primarily by the impact of beat salience on cognitive demands, then groove's effects might only be present in contexts in which it is relevant to reduce cognitive demands. Such contexts could include task parameters that increase cognitive demands (such as the requirement to synchronise to the beat), or individual differences that may make synchronisation more cognitively demanding. Here, we examined whether high beat salience can account for the effects of high-groove music on gait. First, we increased the beat salience of low-groove music to be similar to that of high-groove music by embedding metronome beats in low and high-groove music. We examined whether low-groove music with high beat salience elicited similar effects on gait as high-groove music. Second, we examined the effect of removing the requirement to synchronise footsteps to the beat (i.e., allowing participants to walk freely with the music), which is thought to remove the cognitive demand of synchronizing movements to the beat. We tested two populations thought to be sensitive to the cognitive demands of synchronisation, weak beat-perceivers and older adults. We found that increasing the beat salience of low-groove music increased stride velocity, but strides were still slower than with high-groove music. Similarly, removing the requirement to synchronise elicited faster, less variable gait, and reduced bias for stability, but high-groove music still elicited faster strides than low-groove music. These findings suggest that beat salience contributes to groove's effect on gait, but it does not fully account for it. Despite reducing task difficulty by equalizing beat salience and removing the requirement to synchronise, high-groove music still elicited faster, less variable gait. Therefore, other properties of groove also appear to play a role in groove's effect on gait.

Introduction

Gait impairments are common in Parkinson's disease or stroke, as well as in older populations. One method of improving gait impairments is auditory cueing, a technique in which gait-disordered patients are asked to synchronise footsteps to regularly recurring auditory cues (McIntosh et al. 1997; Zijlstra et al. 1998), such as a metronome or musical beats (for reviews, see Lim et al. 2005; Ghai et al. 2018; Ginis et al. 2018; Moumdjian et al. 2018). In Parkinson's disease, auditory cueing can improve gait by eliciting faster, longer, and less variable strides (Lim et al. 2005), and improve freezing of gait (Moumdjian et al. 2018). Similarly, in stroke, auditory cueing can reduce gait asymmetry and improve gait speed (Hollands et al. 2012). Crucially, however, these improvements do not necessarily persist over the long term after training has ceased (Lim et al. 2005;

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Ginis et al. 2018). Embedding auditory cueing into everyday life beyond the training period may therefore be necessary to achieve long-term improvements (Lim et al. 2005). Music may be a more pleasant stimulus than metronome cues, which could encourage patient compliance with long-term cueing regimens (de Bruin et al. 2010). Indeed, some evidence suggests better outcomes in gait rehabilitation with music than with metronome cues (Dotov et al. 2017). However, music is a more complex auditory cue than metronomes, and has diverse properties which may affect gait (Nombela et al. 2013; Rodger and Craig 2016).

One property of music that affects gait is *groove* (Leow et al. 2014c), commonly defined as 'how much the music makes you want to move' (Madison et al. 2011). In previous work, music rated as high on groove (high-groove music) elicited faster gait than music rated as low on groove (low-groove music) (Leow et al. 2014c). Furthermore, the gait kinematics elicited by high-groove music was similar to those elicited by metronome cues, suggesting that music might be a suitable replacement for metronome cues (Leow et al. 2014c). However, groove is associated with various stimulus characteristics and evokes complex psychological, physiological and behavioral responses (Madison et al. 2011; Janata et al. 2012b; Davies et al. 2013; Witek et al. 2014b), and therefore, the exact mechanisms by which groove affects gait are unclear.

One explanation for groove's effects on gait may be beat salience. Groove in music is associated with strong, salient beats, which may reduce the cognitive demands of finding the beat, as well as predicting oncoming beats, as the music unfolds. Subjective self-reports indicate that high-groove music is perceived to be easier to synchronise than low-groove music (Janata et al. 2012a). In support of this explanation, participants are also better at synchronizing movements (footsteps) to high-groove music than to low-groove music (Leow et al. 2014c; Ready et al. 2019). Higher beat salience in high-groove music could reduce the cognitive demands of synchronisation, resulting in faster gait than low-groove music.

Another possible explanation for the effects of groove on gait is that groove is associated with reward (Vuilleumier and Trost 2015). High-groove music is rated as more pleasurable than low-groove music (Janata et al. 2012a; Witek et al. 2014a), and this reward might elicit more vigorous gait, resulting in faster or longer strides (Park et al. 2019). Indeed, tapping to regular cues embedded in music resulted in weaker dopamine responses in the ventral striatum than tapping to cues alone, a finding interpreted to suggest that tapping to music reduces the effort associated with synchronizing movements to cues (Koshimori et al. 2019). Work in other domains shows that movement in the context of reward is faster and more vigorous (Takikawa et al. 2002; Xu-Wilson et al. 2009), and movement vigor is linked to dopaminergic reward signals (Mazzoni et al. 2007). Music also elicits dopamine release in the reward system (Salimpoor et al. 2011), and thus, rewarding high-groove music might also increase movement vigor through this system. In support of this, research in exercise science indicates that music can increase movement vigor: during fatiguing exercise, athletes expend more energy when listening to music than when exercising in silence (for a review, see Karageorghis and Priest 2012).

To evaluate the first explanation, whether the beat salience of high-groove music affects gait by reducing the difficulty of synchronisation, we performed two experimental manipulations. First, we compared gait during low and high-groove music when beat onsets for both low and high-groove music were emphasized via metronome. We hypothesized that if the effects of groove on gait result solely from easier synchronisation to more salient beats, then explicitly indicating beat onsets in the music should cause low- and high-groove music to elicit similar effects on gait. Second, we assessed whether the ease of synchronizing to high-groove music is responsible for the effects of groove, by removing the requirement to synchronise. Walking without the task of synchronizing to the beat (i.e., free walking) removes any cognitive demands associated with synchronizing footsteps to the beat; the cognitive demands of synchronizing may be higher in low-groove music than in high-groove music, as a result of the beat salience in high-groove music. Therefore, we compared gait when participants were and were not instructed to synchronise their footsteps to the beat. We hypothesized that if high-groove music elicited faster gait than low-groove music even when there was no need to synchronise, then groove's effects on gait do not result solely from greater ease of synchronisation. In addition, we tested these two hypotheses not only in healthy young adults, but also in healthy older adults, as this increases the ecological validity of this work, as older adults are both likely more sensitive to altered cognitive demands during gait (Woollacott and Shumway-Cook 2002), and also more likely to require gait rehabilitation training as a result of acute or chronic conditions such as stroke. Furthermore, as we and others have previously showed that the effect of auditory stimulation on gait depends on beat-perception ability (Leow et al. 2014c; Ready et al. 2019), we also assessed participants' beat-perception ability.

Method

Participants

Twenty healthy young adults from the University of Western Ontario (age range 18–35, M = 21.65 years, 14 females) and 18 older adults (age range 55–82, M = 67.11 years, 13 females) participated. All subjects self-reported normal hearing and no neurological disorders. The study was approved by the Health Sciences Research Ethics Board at the University of Western Ontario. All participants provided written informed consent. Older adults completed the Montreal Cognitive Assessment test to preclude the possibility of mild cognitive impairment: all older adults scored greater than 26 (Nasreddine et al. 2005).

Stimuli

We used a subset of songs from the stimulus database used in our previous study (Leow et al. 2014c). We selected songs which were most consistently rated by previous participants as low groove (five songs) and high groove (five songs). For a list of stimuli and details of the selection method, see the Appendix. In accordance with the previous study (Leow et al. 2014c), the stimulus tempo was determined by having three lab members with musical training tap to the beat of each music clip. Clip loudness was normalized to the same relative volume using Audacity (http://audacity.sourceforge.net). Metronome sequences were created using 50 ms 1 kHz sine tones. All auditory stimuli were trimmed at the beginning so that they began on a beat.

To manipulate beat salience, a trained musician embedded metronome tones to coincide with the beat in each of the ten songs using the program "Garage Band" on a Macintosh computer. The accuracy of metronome tones was reviewed by another trained musician.

Apparatus

Spatio-temporal gait measures were recorded using a Zeno® electronic walkway model Z4 × 16 (Protokinetics, Havertown, PA, USA). The walkway was 579 cm long and 90.2 cm wide with an active sensor area of 488 cm long and 61 cm wide. Data were sampled at 120 Hz and at a spatial resolution of 1.27 cm. The Zeno® electronic walkway and the associated PKMAS post-processing technique produces consistent gait kinematics compared to the alternative GAITRite system (Egerton et al. 2014) Stimuli were played from a desktop PC connected to bookshelf speakers positioned adjacent to the walkway, with sound volume set at a clearly audible and comfortable level for each participant.

General procedure

Gait measurement

In each walking trials described below, participants walked 6 lengths of the 6 m pressure sensor walkway. To obtain steady-state gait, walks started and finished at a pre-marked line 1.5 m beyond the end of the walkway, and participants were required to continue stepping as they turned at the pre-marked line (Hollman et al. 2010). This resulted in more than 50 strides for all participants for each individual trial. This number of steps collected on similar pressure sensor walkways is considered sufficient for determining the primary gait parameters of interest (Hollman et al. 2010), including for reliable estimations of stride variability, which requires a minimum of 30 steps (i.e., 15 strides) (Galna et al. 2013).

Baseline gait measurement

First, each participant's baseline preferred step tempo (number of steps per minute) was obtained as participants walked 6 lengths of the pressure sensor walkway with no auditory stimuli present.

Stimulus selection

Next, we customized stimulus selection based on individual participant ratings of our stimulus set. As the experience of groove is subjective, this helped to ensure that each participant would experience the high-groove and low-groove songs as genuinely high and low in groove. Participants rated all clips from the stimulus list on perceived groove, familiarity, arousal, and enjoyment on a ten-point Likert scale. The rating scale items were as follows: (1) Groove: How much did the music make you want to move? 1 = low sensation to move, 5.5 = neutral, 10 = high sensation to move. (2) Familiarity: How familiar are you with the music clip? 1 = not at all familiar, 5.5 = neutral, 10 = very familiar to me. (3) Enjoyment: How enjoyable is this piece of music? 1 = not at all enjoyable, 5.5 = neutral, 10 = very enjoyable. (4) Arousal: 1. very relaxing, 5.5 neural, 10 = very stimulating. To reduce the influence of differing levels of familiarity on gait, only songs rated low on familiarity were included. Participants rated the ten songs both with and without embedded metronome tones to evaluate the possibility that embedding the metronomes altered the groove properties of the song. Based on individual ratings, a customized stimulus list was prepared that had the following four conditions, used in the walking task: (1) two high groove, metronome-embedded songs, (2) two low groove, metronome-embedded songs, (3) two high-groove, no metronome songs, (4) two low groove, no metronome songs. To estimate each participant's ability to synchronise to auditory cues outside the context of music, the stimulus list also included metronome sequences (consisting of 50 ms 1 kHz sine tones). All stimuli were altered to participants' preferred step tempo using Audacity's "Change Tempo" function, which does not alter the pitch qualities of the stimuli (Fujii and Schlaug 2013).

Beat alignment test

After completing the ratings task, participants completed the beat alignment test from the Goldsmiths Music Sophistication Index v1.0 (Müllensiefen et al. 2012), which is modelled after the original Beat Alignment Test (Iversen 2008). The beat alignment test assesses participants' ability to perceive the beat in music without requiring participants to move to the beat. Participants decided whether metronome beeps superimposed over instrumental music clips were correctly aligned with the perceptual beat of that clip. Beeps were aligned with the beat in four trials. The remaining trials contained either (1) a tempo error (eight trials): beeps were 2% faster or slower than the true beat tempo, or (2) phase error (five trials): beeps were ahead of the actual beat by 10% or 17.5% of the length of the beat interval. Participants completed three practice trials and 17 test trials. Stimulus order was randomized for each participant. After listening to the entire clip, participants judged whether the beeps were in time with the beat by pressing the "y" key to indicate yes and the "n" key to indicate no. Participants also rated their confidence in their answer (1 = not sure, 2 = somewhat sure, 3 = very sure). We selected the beat alignment test instead of other more comprehensive measures of beat perception (e.g., BAASTA (Farrugia et al. 2012), Harvard BAT (Fujii and Schlaug 2013)), because it is brief, and easy to implement and interpret.

Walking task

After completing the beat alignment test, participants began the walking task. All participants completed a total of 20 walking trials. In each trial, participants walked six lengths of the gait mat, similar to the baseline gait measurements. All experimental conditions for the walking task are shown in Table 1. In half of the trials, participants were instructed to try to synchronise their footsteps to the beat of the stimulus (synchronise trials). In the remaining half of the trials, participants were instructed to walk freely in the presence of the musical stimuli in whatever way felt most natural (free walking trials). The 20 walking trials consisted of 16 music trials (8 synchronise trials, 8 free walking trials) and 4 metronome trials (2 synchronise trials, 2 free walking trials). The 16 music trials consisted of 4 music conditions: low groove no metronome (2 trials), high groove no metronome (2 trials), low groove metronome embedded (2 trials), high groove metronome embedded (2 trials). Trials for each stimuli condition (music, metronome) and each instruction condition (free walking, synchronise) were presented in random order (i.e., none of the experimental conditions were blocked). Participants were allowed as much time as needed before starting to walk in every trial. Note that the metronome only trials were not analysed, the inclusion of metronome only trials were in keeping with our previous study design (Leow et al. 2014c).

Table 1 Experimental conditions. trials were run in random order

Gait instructions	Stimuli
Free walking	Metronome alone
	Low groove, no metronome
	Low groove, embedded metronome
	High groove, no metronome
	High groove, embedded metronome
Synchronise	Metronome alone
	Low groove, no metronome
	Low groove, embedded metronome
	High groove, no metronome
	High groove, embedded metronome

Data analysis

Synchronisation performance

Synchronisation was assessed by evaluating how well the phase of step onsets matched the phase of beats onsets in the stimuli. For purposes of analysis, we used step onsets (first contact time of each step) to examine synchronisation (McIntosh et al. 1997). Phase shifts of beat onsets are common in music, and therefore, cannot be reliably estimated from an average tempo. Beat onset times were therefore objectively estimated with beat-tracking software (BeatRoot) (Dixon 2007). Synchronisation performance was assessed by quantifying phase-matching performance (how well the phase of the steps matched the phase of the beats). It was not meaningful to quantify period-matching performance as the stimuli tempo were all matched to each participants step tempo. Analyses were restricted to the instructed condition due to excessive synchronization variability (approximately half of the R-vectors shorter than 0.45) in the uninstructed condition. Synchronisation variability was estimated using circular variance.

Spatio-temporal gait parameters

Gait kinematics were first obtained using ProtoKinetics Movement Analysis Software (PKMAS) and then exported to tab delimited files for collation with custom written LabVIEW programs. Gait kinematics reflecting gait speed**,** gait variability and bias for stability were selected for analysis. **Gait speed parameters** were stride velocity, length, and time. Stride velocity is the distance covered per unit time (m/s) for every two consecutive steps, and is determined by stride length and stride time. Stride length was defined as the anterior–posterior distance from the first contact location of one step to the first contact location of the next ipsilateral step. Stride time was defined as the time interval between the first contact time of one step to the first contact time of the next ipsilateral step. Stride time is related to cadence (steps per minute): stride time = 60 divided by cadence. Thus, shorter stride times are equivalent to a higher cadence (taking more strides per minute requires that the time per stride be less). Changes in stride velocity can result from changes in stride length (e.g., longer steps), changes in stride time (more steps), or both. **Gait variability** is a sensitive index of attentional demands during gait—the larger the attentional demands during gait, the more variable the gait parameters are (Al-Yahya et al. 2011). We examined gait variability using the coefficient of variation (standard deviation of that gait parameter normalized to the mean gait parameter) for stride velocity, stride time, and stride length. **Bias for stability**, which relates to balance control, was determined from double support time (% of time that both feet were simultaneously in contact with the ground) and stride width (lateral distance from heel center of one footprint to the line of progression formed by two consecutive footprints of the opposite foot). Increases in double support time and stride width indicate that gait has changed to become more supportive, and these increases occur during dual-task situations (Woollacott and Shumway-Cook 2002; Nadkarni et al. 2010).

To assess how gait changes during the experimental conditions compared to baseline uncued walking, we calculated the difference score for each parameter relative to uncued walking. For each participant, we subtracted the average gait parameters in each experimental condition from the average gait parameters in the baseline condition (Rochester et al. 2005). Then, to minimize the effect of individual differences (e.g., effect of leg length) on group averages, we normalized the change scores to the baseline gait parameters of each participant.

$$\textit{Normalized Change Score} = \frac{\textit{Gait Parameter} - \textit{Baseline Gait Parameter}}{\textit{Baseline Gait Parameter}}$$

Statistical analyses

The first hypothesis was that the effect of high-groove music on gait relied on easier synchronisation to more salient beats. To address this hypothesis, we tested how gait during synchronisation trials were affected when beat onsets for both low and high-groove music were emphasized via metronome, using ANOVAs with the factors Age (Young, Older) and Beat Perception Ability (Weak Beat-perceivers, Strong Beat-perceivers) and within-subject factors Groove (Low Groove, High Groove) and Beat Salience (No Metronome Embedded, Metronome Embedded). If this hypothesis is supported, we predicted significant Metronome x Groove interactions where embedding metronome tones into low-groove music would alter gait to be more similar to that with high-groove music.

The second hypothesis was that the effect of groove would persist despite absence of instruction to synchronise, regardless of experimentally manipulated beat salience by embedding metronomes. To address this hypothesis, we ran ANOVAs with the between-subjects factors Age (Young, Older) and Beat Perception Ability (Weak Beat-perceivers, Strong Beat-perceivers) and within-subject factors Groove (Low Groove, High Groove), and Beat Salience (No Metronome Embedded, Metronome Embedded) for the free-walk trials. If this hypothesis is supported, we predicted significant main effects of groove despite the absence of instructions to synchronise to the beat.

These two ANOVAs were conducted on each gait parameter (stride length, stride time, stride velocity, stride length variability, stride time variability, stride velocity variability, double support time, and stride width). Significant F-values were followed-up by separate ANOVAs and t tests (Bonferroni-corrected where necessary) to interpret differences between conditions. Note that the Metronome Only trials were not included in these analyses: we plotted them in Fig. 2 for visual comparison only.

Results

BAT perception scores

BAT scores were the proportion of correct responses across the 17 trials. Scores ranged from 0.29 to 1, M = 0.72, SD = 0.16. No significant interaction was found between age and BAT scores, no reliable differences in beat perception ability in our sample of young and older adults.

Baseline gait parameters

Participants' average baseline gait parameters without auditory cues are summarized in Table 2. Older adults did not differ significantly from young adults in gait speed parameters (stride velocity, stride time, stride length) or gait variability (coefficient of variability of stride velocity, stride time, stride length). Older adults

Table 2 Mean and standard deviation (in brackets) of baseline gait parameters in young and older adults

Gait parameter	Uncued walking	
	Younger ($n=20$)	Older ($n=18$)
Gait speed		
Stride velocity (cm/s)	114.4 (14.5)	120.5 (19.0)
Stride length (cm)	122.9 (10.4)	128.3 (11.8)
Stride time (s)	1.08 (.08)	1.08 (.10)
Variability (coefficient of variation)		
Stride velocity variability	4.23% (1.02%)	4.35 (1.15%)
Stride length variability	3.64% (0.95%)	3.16% (1.06%)
Stride time variability	2.50% (0.79%)	2.25% (0.83%)
Bias for stability		
Stride width (cm)	8.5 (2.2)	7.4 (2.6)
Double support time (% gait cycle)***	24.3% (3.63%)	29.02% (3.31%)

Asterisks indicate significant differences between young and older adults (** indicates $p<.01$, *** indicates $p<.005$)

did, however, show significantly greater bias for stability in terms of longer double support time (young adults: $M=24.29\pm3.63$, older adults: 29.02 ± 3.31 than young adults, $t(36)=4.18$, $p<0.001$).

Effect of increasing beat salience in low-groove music

Synchronisation performance

To address the first hypothesis that the effect of groove was due to greater ease of synchronisation, we evaluated how explicitly outlining the beat by embedding metronome tones in low-groove music would affect synchronisation performance. We ran Metronome x Groove x Beat Perception x Age ANOVAs on circular variances for trials where participants were instructed to synchronise to the beat, focussing on Metronome x Groove interactions. There was a main effect of Groove, $F(1,30)=10.32$, $p=0.003$, partial η-squared = 10.32, which was qualified by a Metronome x Groove interaction, $F(1,30)=23.55$, $p=0$, partial η-squared = 23.55. The Metronome x Groove interaction was driven by the effect of **larger** circular variance after embedding metronomes onto low-groove music $t=4.907$, $p_{bonf}=4.656e\text{-}5$, mean difference = 0.258. In contrast, embedding metronome tones somewhat reduced circular variance for high-groove music $t=-2.491$, $p_{bonf}=0.094$, mean difference = − 0.131.

Gait

To address the first hypothesis that increasing beat salience by embedding metronome cues in low-groove music would cause low and high-groove music to elicit similar effects on gait, we ran Metronome x Groove x Beat Perception x Age ANOVAs on gait parameters for trials where participants were instructed to synchronise to the beat, focussing on Metronome x Groove interactions. ANOVA results are shown in Table 3.

Gait speed

As previously shown (Ready et al. 2019), strides overall slowed and shortened when participants were instructed to synchronise to the beat (see Fig. 1 top panel). High-groove music elicited less slowing and shortening of strides than low-groove music (see Fig. 1), as shown by significant main effects of groove on stride velocity [$F(1, 34)=17.373$, $p=1.995$ E-4, partial η-squared = 0.03] and stride time [$F(1, 34)=12.614$, $p=0.001$, partial η-squared = 0.27]. The effect of groove on gait speed depended on beat-perception, as shown by a Groove x Beat Perception interaction for stride velocity [$F(1, 34)=6.89$, $p=0.013$, partial η-squared = 0.17] and stride time [$F(1, 34)=5.66$, $p=0.02$, partial η-squared = 0.14]. The effect of groove was particularly evident for poor beat-perceivers who showed more slowing of gait (slower stride velocity, longer stride time) when synchronizing to low-groove music. In contrast to beat-perception, age had no reliable effect on all measures of gait speed (see Table 3).

Embedding the metronome into music had different effects on stride velocity for low and high-groove music [Metronome x Groove interaction for stride velocity, $F(1, 34)=5.963$, $p=0.02$, partial η-squared = 0.14]. Increasing beat salience by embedding metronome beats increased stride velocity for low-groove music (Mean Difference = 0.057, [0.093, 0.02], $t=4.203$, pbonf = 4.909E-4) but did not significantly increase stride velocity for high-groove

Table 3 Results of Metronome x Groove x Beat Perception x Age Group ANOVAs run on gait variability parameters, for trials where participants were instructed to synchronise to the music

	Gait speed						Gait variability						Bias for support			
	Stride velocity		Stride time		Stride length		Stride Velocity Variability		Stride time variability		Stride Length Variability		Double support		Stride Width	
	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p
Met	**13.4**	**9.E-04**	3.2	0.1	1.3	0.3	0.6	0.4	2.4	0.1	0.2	0.6	0.0	1.0	0.1	0.7
Met x Age	1.4	0.2	1.3	0.3	0.0	0.9	1.9	0.2	0.8	0.4	2.6	0.1	**9.4**	**4.E-03**	0.1	0.7
Met x BP	**4.3**	**5.E-02**	1.2	0.3	0.2	0.7	0.0	0.9	0.4	0.5	1.1	0.3	1.4	0.2	2.E-02	0.9
Met x Age x BP	1.2	0.3	1.2	0.3	0.0	1.0	2.1	0.2	1.3	0.3	1.0	0.3	3.9	0.1	1.E-03	1.0
Groove	**17.4**	**2.E-04**	**12.6**	**1.E-03**	0.6	0.4	14.7	**5.E-04**	17.9	**2.E-04**	0.4	0.5	**7.8**	**8.E-03**	3.4	0.1
Groove x Age	1.5	0.2	1.5	0.2	0.2	0.7	0.6	0.5	1.4	0.3	0.2	0.7	0.5	0.5	1.8	0.2
Groove x BP	**4.8**	**4.E-02**	**7.2**	**1.E-02**	0.2	0.6	0.4	0.5	0.3	0.6	0.4	0.5	0.2	0.7	0.7	0.4
Groovex Age x BP	3.8	0.1	1.3	0.3	0.7	0.4	0.0	1.0	0.5	0.5	0.3	0.6	0.7	0.4	2.2	0.1
Met x Groove	**6.0**	**2.E-02**	3.1	0.09	0.1	0.8	0.0	0.8	1.1	0.3	3.0	0.1	1.4	0.3	3.8	0.1
Met x Groove x Age	0.6	0.4	0.5	0.5	2.3	0.1	3.6	0.1	0.5	0.5	**10.6**	**3.E-03**	0.8	0.4	4.E-05	1.0
Met x Groove x BP	1.2	0.3	1.7	0.2	1.1	0.3	1.0	0.3	0.2	0.6	**5.5**	**2.E-02**	0.6	0.4	1.E-02	0.9
Met x Groove x Age x BP	0.4	0.5	0.8	0.4	0.1	0.7	1.3	0.3	0.5	0.5	2.0	0.2	0.1	0.8	0.3	0.6
Age	0.1	0.8	2.9	0.1	0.9	0.3	0.3	0.6	0.2	0.7	1.5	0.2	0.4	0.5	0.1	0.8
BP	1.3	0.3	**5.8**	**2.E-02**	0.4	0.5	**10.0**	**3.E-03**	**5.6**	**0.0**	**9.4**	**4.E-03**	0.7	0.4	5.2	3.E-02
Age x BP	0.1	0.7	1.9	0.2	2.4	0.1	0.0	0.9	0.2	0.7	**7.6**	**9.E-03**	0.6	0.4	0.0	1.0

BP Beat Perception, *Met* Metronome, *Age* AgeGroup

music (metronome high groove versus no metronome high groove, Mean Difference = − 0.006 [− 0.042, 0.031], t=− 0.416, pbonf = 1). With metronome embedded, stride velocity with low-groove music no longer differed significantly from high-groove music without metronome embedded (t= 1.79, pbonf = 0.47), or from high-groove music with metronome embedded (t = 2.00, pbonf = 0.30).

Gait variability

Overall, gait was more variable when synchronizing than at baseline (see Fig. 1). Weak beat-perceivers showed more variable gait when instructed to synchronise to the beat, as shown by significant main effects of beat perception ability on stride velocity variability, stride time variability, and stride length variability, see Table 3. Low-groove music tended to increase gait variability more than high-groove music, as shown by the main effect of groove on stride velocity variability and stride time variability (see Table 3).

Embedding metronome tones had no significant main effect on stride velocity and stride time variability. For stride length variability however, there was a Metronome x Groove x Beat Perception interaction, F(1,34) = 5.54, p = 0.024, partial η-squared = 0.01. Follow-up Metronome x Groove x Age Group ANOVAs were run separately for strong and weak beat-perceivers. For weak beat-perceivers, outlining beat onsets with the metronome cues resulted in smaller increases in stride length variability, (Metronome x Groove, F(1,16) = 5.303, p = 0.035, partial η-squared = 0.03), particularly for older adult weak beat-perceivers [Metronome x Groove x Age Group interaction, F(1,16) = 6.94, p = 0.018, partial η-squared = 0.03]. Older adult weak beat-perceivers showed a larger increase in stride length variability (mean difference in stride length variability than older adult strong beat-perceivers, (mean difference: − 1.06 [− 1.76, − 0.36], t = − 4.24, pbonf = 9.026 E-4). In contrast, young adults showed little difference in stride length variability whether they had strong or poor beat perception (mean difference = − 0.025 [− 0.69, 0.64], t = 0.10, pbonf = 1).

Bias for support

Figure 1 shows that synchronising to high-groove music results in smaller increases in bias for support than with low-groove music, as shown by a main effect of groove for double support time, [F(1, 34) = 7.841, p = 0.008, partial η-squared = 0.187]. Weak beat-perceivers showed overall larger increases in stride width (mean stride width increase = 0.236, [0.102, 0.370]), than strong beat-perceivers (mean stride width increase = 0.023, [− 0.111, 0.157]), as shown by a main effect of beat perception on stride width [F(1, 34) = 7.132, p = 0.011, partial η-squared = 0.155] (see Fig. 1).

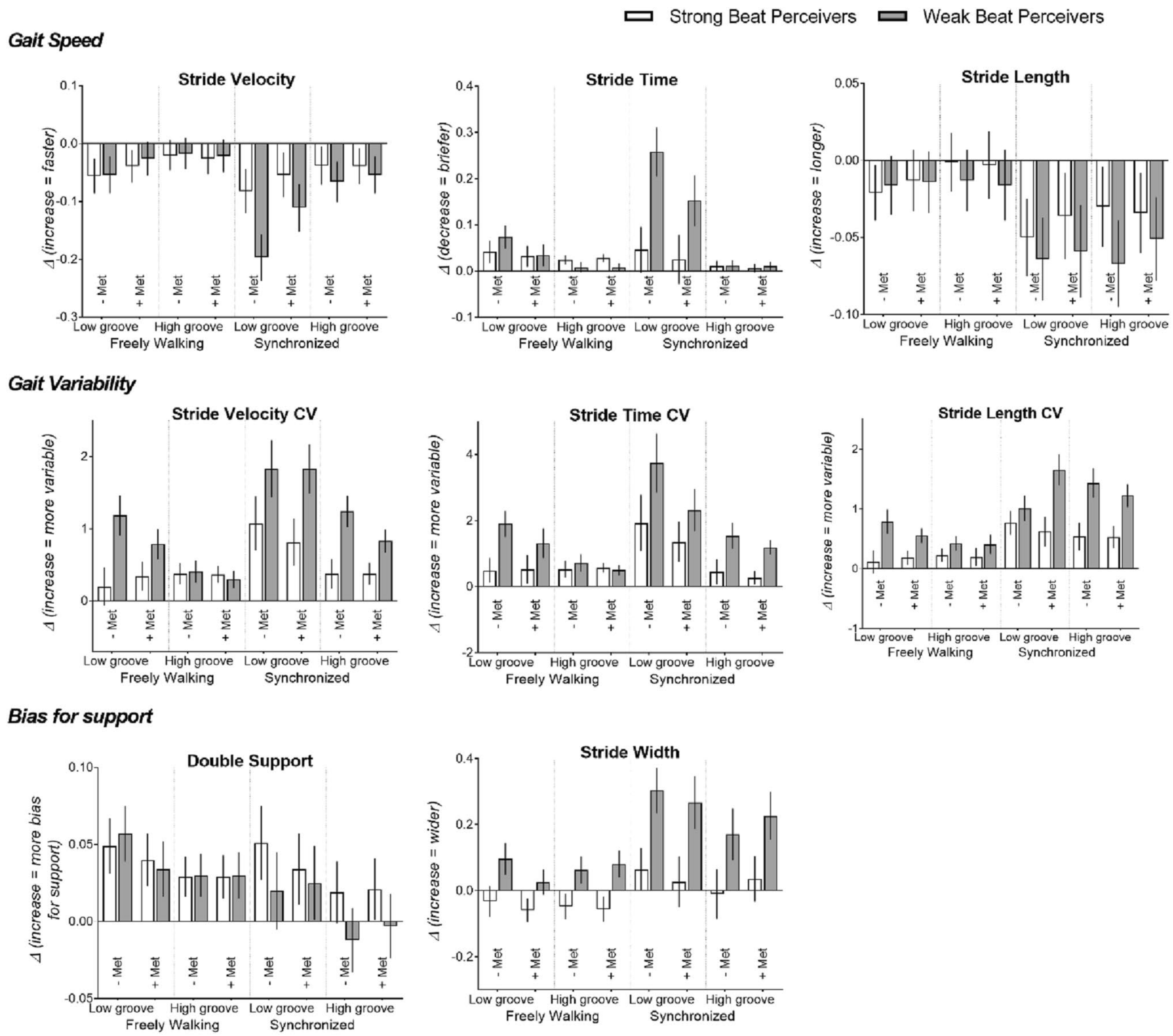

Fig. 1 Normalized mean change scores in gait parameters relative to uncued walking (values close to zero indicate similar gait to baseline, values above zero indicate increases compared to baseline, values below zero indicate decreases compared to baseline). Data from strong beat-perceivers are shown in clear bars, and weak beat-perceivers shown in grey bars. Participants were either not instructed to synchronise (i.e., freely walk with the music —left side of graphs), or instructed to synchronise to the beat (synchronised—right side of graphs). Low-groove and high-groove music either had metronome beats embedded (+Met) and did not have metronome beats embedded (− Met). Data are collapsed across young and older adults. Error bars are standard errors of the mean

Embedding metronome tones did not significantly modulate the effect of groove for both stride width and double support time, as shown by a non-significant Metronome x Groove interaction (see Table 3). For double support time there was a Metronome x Age interaction, where older adults showed a non-significant tendency to decrease double support time with metronome (Mean Difference=− 0.02 [− 6.07e-3, − 0.04], t=-2.13, pbonf=0.25), unlike young adults, who tended to increase double support time with metronome (Mean Difference=0.02 [0.04, 4.93e-3], *t*=− 2.23, pbonf=0.19.

Effect of groove without the requirement to synchronise

To address the second prediction that groove would still affect gait after removing the requirement to synchronise, we ran Groove x Metronome x Beat Perception x Age Group ANOVAs on the freely walking conditions. We focussed on the main effect of groove to address the hypothesis. ANOVA results are shown in Table 4.

Table 4 Results of Metronome x Groove x Beat Perception x Age Group ANOVAs run on gait variability parameters, for trials where participants were instructed to freely walk with the music

	Gait speed						Gait variability						Bias for support			
	Stride velocity		Stride time		Stride length		Stride velocity variability		Stride time variability		Stride length variability		Double support		Stride width	
Factors	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p
Met	1.1	0.3	1.1	0.3	0.1	0.8	0.5	0.5	0.7	0.4	0.5	0.5	2.9	0.1	2.5	0.1
Met x Age	0.4	0.5	0.0	0.9	0.5	0.5	0.2	0.6	0.0	1.0	0.0	1.0	2.0	0.2	6.5	**0.0**
Met x BP	0.2	0.7	0.6	0.5	0.1	0.8	1.5	0.2	1.1	0.3	1.0	0.3	0.5	0.5	0.1	0.8
Met x Age x BP	0.0	1.0	0.1	0.7	0.1	0.7	0.2	0.7	0.0	1.0	1.9	0.2	1.2	0.3	3.8	0.1
Groove	**7.0**	**0.0**	**6.4**	**0.0**	**1.9**	**0.2**	**4.1**	**0.1**	**4.4**	**0.04**	1.4	0.3	**4.9**	**0.03**	0.0	0.9
Groove x Age	0.0	1.0	0.8	0.4	0.7	0.4	0.4	0.6	0.7	0.4	0.5	0.5	0.1	0.8	3.3	0.1
Groove x BP	0.0	0.9	2.4	0.1	1.7	0.2	7.8	**0.0**	**5.3**	**0.03**	3.6	0.1	0.0	1.0	0.3	0.6
Groove x Age x BP	0.0	1.0	1.1	0.3	0.9	0.4	0.1	0.8	1.8	0.2	0.5	0.5	0.2	0.7	0.0	0.8
Met x Groove	**4.3**	**0.046**	1.7	0.2	1.3	0.3	0.1	0.8	0.2	0.6	0.1	0.8	1.6	0.2	4.3	0.1
Met x Groove x Age	0.0	1.0	0.2	0.7	0.4	0.6	0.8	0.4	0.2	0.7	3.6	0.1	0.2	0.6	0.3	0.6
Met x Groove x BP	0.1	0.7	0.4	0.6	0.1	0.7	0.8	0.4	0.2	0.7	0.7	0.4	0.3	0.6	1.9	0.2
Met x Groove x Age x BP	1.4	0.3	0.0	1.0	3.6	0.1	0.8	0.4	0.0	1.0	2.6	0.1	0.7	0.4	0.6	0.4
Age	0.0	0.9	0.7	0.4	0.3	0.6	3.4	0.1	4.2	0.1	5.2	0.0	4.2	0.1	0.5	0.5
BP	0.0	0.9	0.0	1.0	0.0	0.9	4.5	0.0	4.3	0.1	5.4	0.0	0.0	1.0	4.9	**0.0**
Age x BP	0.5	0.5	0.5	0.5	0.8	0.4	2.8	0.1	1.2	0.3	6.0	0.0	0.1	0.8	1.2	0.3

BP Beat Perception, *Met* Metronome, *Age* AgeGroup

Even without instructions to synchronise, high-groove music still elicited faster, less variable strides and reduced bias for support than low-groove music (Fig. 2, white versus pink columns), as there was a significant main effect of Groove on **gait speed parameters**: [stride velocity: F(1,34) = 7.00, p = 0.012, partial η-squared = 0.17, and stride time F(1,34) = 6.43, p = 0.016, partial η-squared = 0.16], **gait variability** [stride velocity variability: F(1,34) = 5.12, p = 0.04, partial η-squared = 0.11; stride time variability, F(1,34) = 4.44, p = 0.04, partial-η squared = 0.11], and **bias for support** [double support time [F(1,34) = 4.90, p = 0.03, partial-η squared = 0.13].

Discussion

The three main results from the current study are as follows. First, emphasizing the beat in low-groove music by embedding metronome beats resulted in faster, more frequent strides. Second, even without instructions to synchronise to the beat, high-groove music still resulted in faster, less variable strides than low-groove music. We speculate that although the high beat salience of high-groove music reduces the cognitive demands of synchronizing to the beat, additional properties of groove also contribute to its effects on gait. These results are discussed below.

Effect of embedding metronome beats into low- and high-groove music

Here, we found that increasing beat salience of music by embedding Mets had larger effects on low-groove music than on high-groove music. Emphasizing the beats in low-groove music elicited faster, more frequent strides during synchronisation than low-groove music without Met cues. This is consistent with the idea that low-groove music elicits slower strides during synchronisation because low beat salience makes it more difficult to synchronise to the beat, resulting in slower strides. Enhancing beat salience by embedding a Met makes synchronizing to low-groove music less difficult, resulting in smaller gait decrements. In contrast, embedding metronome beats onto high-groove music did not reliably affect most gait parameters, perhaps because the high beat salience inherent in high-groove music rendered the presence of the metronome beats redundant. In addition to the

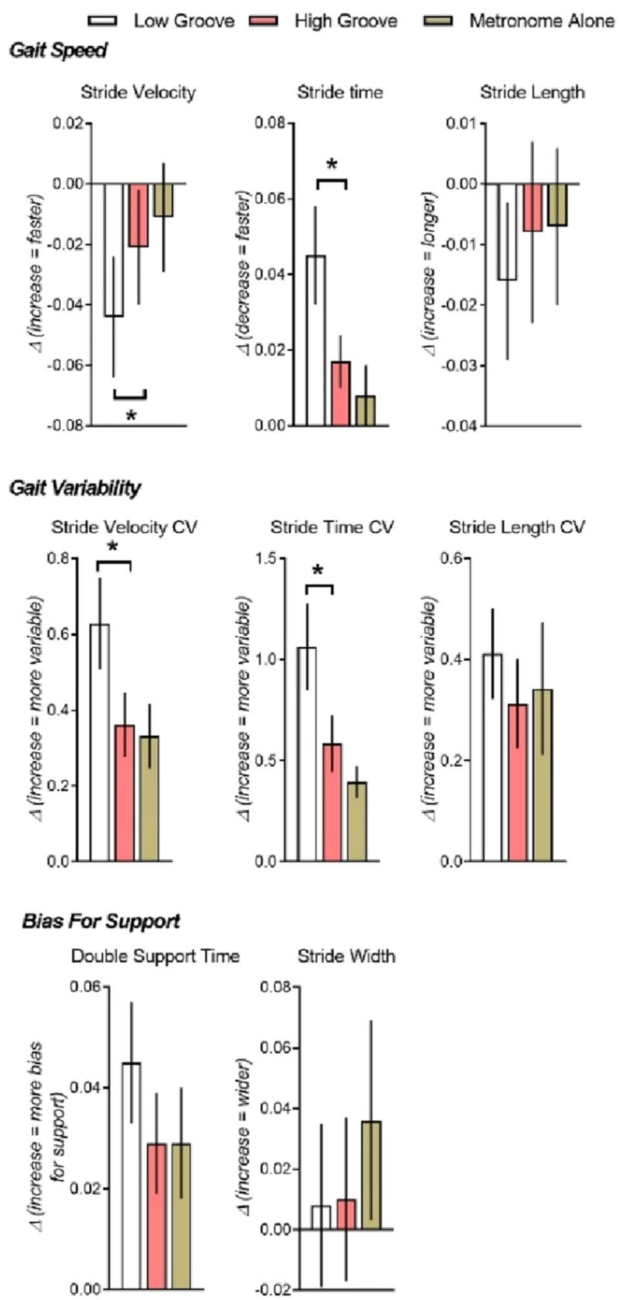

Fig. 2 How groove affected gait when walking without instructions to synchronise. Mean normalized change scores as a proportion of baseline uncued walking in gait parameters (error bars = SEM), in trials where participants were not instructed to synchronise, collapsed across young and older adults, across good and poor beat-perceivers, and across conditions with and without metronome embedded. Metronome only conditions are presented only for visual comparison, and were not used in any statistical analyses

greater beat salience already inherent in high-groove music, and high-groove music has greater density of sound events that often occur at subdivisions of the beat interval (Madison et al. 2011; Stupacher et al. 2016), and could thus provide additional cues from which the beat can be predicted.

Groove in music alters gait even without the requirement to synchronise

Even after removing instructions to synchronise, high-groove music still elicited faster, less variable strides and smaller bias for support than low-groove music. The effects of groove therefore cannot be caused solely by the high beat salience reducing cognitive demands of synchronisation, although we note that we did not directly measure or manipulate cognitive demands of synchronisation (for example, by asking participants to complete a dual-task), and thus our inferences made here with regards to cognitive demands are speculative. We suggest that the differential effects of high and low-groove music on gait may be related to the rewarding properties of high-groove music. Generally, music is thought to be rewarding (Salimpoor et al. 2013) and reward increases movement vigor (Xu-Wilson et al. 2009). Furthermore, high-groove music is rated as more pleasurable and more rewarding than low-groove music (Janata et al. 2012a; Witek et al. 2014a; Bowling et al. 2019). High-groove music also increases noradrenergic responses more than low-groove music (Bowling et al. 2019). In support of the idea that music-associated rewards can influence movement, faster or more vigorous movements have been observed in the context of music (Karageorghis and Priest 2012; Fritz et al. 2013). The higher reward responses associated with high-groove music could provide another mechanism, in addition to beat salience, by which high groove elicits faster gait.

Effect of removing instructions to synchronise to the beat

Replicating previous results (Leow et al. 2018; Ready et al. 2019), instructions to synchronise to the beat elicited slower, more variable strides and increased the bias for support compared to walking without instructions to synchronise. This pattern of results was evident both in strong and weak beat-perceivers, and in young and older adults. Hence, at least in neurologically intact young and older adults, within the context of a single session, synchronisation to rhythmic auditory cues may not be beneficial in increasing gait speed and stride length. Our findings are consistent with previous studies that show faster and longer strides in rhythmic auditory cueing studies when participants were not explicitly instructed to synchronise to the beat (Benoit et al. 2014), or when participants failed to synchronise their step tempo to the cue tempo (Wittwer et al. 2012).

It is also noteworthy that in all of cueing conditions with the stimuli tempo set to self-selected walk cadence, strides were not significantly longer, more frequent, less variable, or less biased for support compared to baseline uncued walking (i.e., when participants walked at a self-selected pace without any auditory stimuli). There are several potential explanations for this. First, changes in gait parameters observed in the majority of previous studies have been shown with stimuli set at tempi that differs from self-selected gait cadence (Thaut et al. 1996). Previous work similarly shows that in adults with healthy gait, synchronizing footsteps to Met cues set at preferred tempo does not elicit faster, longer, or less variable gait (Hausdorff, 2009; Hove et al. 2012). Second, in healthy gait, gait kinematics are already optimized to minimize energy expenditure (Donelan et al. 2001, 2002). More energy is expended when walking with faster or longer strides than walking at one's preferred stride speed and stride length (Donelan et al. 2001, 2002). Third, as we did not explicitly instruct our participants to alter their strides, there was no reason for participants to choose faster or longer strides in exchange for sub-optimal energy expenditure. Synchronisation may only elicit longer or faster strides in disordered gait, when disordered gait kinematics elicit sub-optimal energy expenditure, such as in Parkinson's disease (Katzel et al. 2012; Maggioni et al. 2012). Fourth, even in gait-disordered populations, explicit intention to lengthen or speed up their strides during cueing might play an important role. For example, one study has found that stride length increased only when patients were explicitly instructed to lengthen their strides during cueing, and not when patients walked to the cues without instructions to lengthen their strides (Baker et al. 2007). In this current study, we were interested in whether gait is altered by the stimulus properties, and thus we ensured that participants were naive to the study purpose and provided no instruction to alter stride kinematics.

Effect of beat-perception and age on gait when synchronizing to music

Previous work suggests that individual differences in sensorimotor timing abilities, such as beat perception, influence gait responses when individuals are instructed to synchronize footsteps to the beat (Leow et al. 2014c; Dalla Bella et al. 2017; Ready et al. 2019). We found that weak beat-perceivers took slower, more variable strides, and showed a larger bias for support than strong beat-perceivers, particularly when synchronizing to low-groove music. In contrast to the effect of beat perception, we did not find a clear effect of age on the majority of our gait parameters. At baseline, our sample of older adults showed larger double support time, but did not differ significantly from young adults in other gait parameters tested. The only effect of age was on stride length variability, and this effect depended on beat perception. Older adults with weak beat-perception tended to show more increases stride length variability than older adults with strong beat-perception, unlike young adults who did not show significant differences in stride length variability regardless of beat-perception ability. Older adults also tended to reduce double support time with metronome embedded than without metronome embedded, indicating potential beneficial effects of embedding metronome cues to reduce double support time, which was also the only gait parameter that showed age-related differences at baseline in our sample. The finding that both young and older adults showed slower and more variable gait when required to synchronise to music suggests that clinicians using music-based rhythmic auditory synchronisation should consider individual capacity in sensorimotor timing abilities such as beat-perception to avoid inadvertent negative effects on gait (Bella et al. 2017), particularly in poor beat-perceivers, and older adults who show increased bias for support.

Clinical Implications

Beat-perception ability may influence benefits from auditory cueing in rehabilitation

Here, we show that in healthy young and older adults, poor beat-perceivers also show poorer gait responses when synchronizing movements to auditory cues, consistent with previous reports in healthy (Leow et al. 2014c; Ready et al. 2019) and gait-disordered populations (Dalla Bella et al. 2017; Cochen De Cock et al. 2018; Dalla Bella et al. 2018). These individual differences are likely similarly present in gait-disordered populations, and thus might also limit the likelihood of gait improvement from auditory cueing. We speculate that individual differences in sensorimotor timing abilities such as beat-perception may partially explain variability in auditory cueing efficacy (Nombela et al. 2013): although many studies show improved gait with cueing (Kritikos et al. 1995; Thaut et al. 1999, 2007; Rochester et al. 2009), other studies do not (Cubo et al. 2004; Wittwer et al. 2013). Individual differences in sensorimotor timing abilities such as beat-perception may partly explain previous findings of difficulty synchronizing footsteps to metronome beats (Ford et al. 2007; Roerdink et al. 2007, 2009). The current findings indicate for poor beat-perceivers, synchronizing may produce a cost, rather than a benefit. Innovative methods where music cues are altered in real-time to synchronise with participant steps (Hove et al. 2012) might thus have utility in compensating for difficulty with synchronisation in individuals with poor beat-perception and/or poor synchronisation capacity.

High-groove music as an optimal stimulus in gait rehabilitation

The current results suggest that high-groove music might be an optimal stimulus to elicit faster and longer strides in gait rehabilitation. Such benefits of high-groove music were also evident even when there was no requirement to synchronise to the beat, suggesting that greater ease of synchronisation to high-groove music is not the sole factor driving improved gait with high-groove music: rewarding and/or movement-inducing properties of high-groove music might also improve gait. However, as this and previous studies (Leow et al. 2014a, b) were run on neurologically intact young and older adults, it is unknown whether groove will also alter gait in gait-disordered populations who often also show mood disorders which may reduce their capacity to derive pleasure from music (e.g., between 18.4 and 45.7% of PD patients experience anhedonia (Isella et al. 2003; Loas et al. 2014). Despite this, recent studies suggest promising effects of incorporating music in therapeutic contexts. For example, a 12-week gait training programme which incorporated music improved mood in Parkinson's disease patients (Burt et al. 2020). Patients with multiple sclerosis also reported less physical and cognitive fatigue when walking with music stimuli than with Met stimuli (Moumdjian et al. 2019). Future studies are needed to explore the potential benefits of motivational/movement-inducing properties of high-groove music in clinical populations.

Conclusion

The present findings show that despite equalizing the beat salience of low- and high-groove music, and despite removing the requirement to synchronise, high-groove music still elicited faster gait and smaller bias for support than low-groove music. We speculate that these results suggest that groove affects gait not only because its high beat salience reduces the cognitive demands of synchronizing, but also because its additional properties of groove, such as its rewarding properties may alter movement vigor, both in young and older adults. Such findings might have implications for the judicious design of music-based rehabilitation, which shows promise in improving outcomes in healthy and clinical populations (Sihvonen et al. 2017).

Appendix A

Stimulus selection

For a previous study in our lab, a database of 49 song clips was compiled. Eleven lab members rated these clips in terms of groove and familiarity on a 10-point Likert scale. Stimuli rated as greater than 5 on familiarity were discarded. Based on the ratings, a set of 10 songs were selected, five low groove, five high groove. The set of ten clips are listed below. Tempos for these ten clips were estimated by having four musically trained lab members manually tap to the beat on a USB-connected keyboard. The average tempo from the four lab members for each song was used. Participants walked with these songs with or without Met tones embedded.

Groove	Song Title	Artist	Album
High groove	Remember	ATB (André Tanneberger)	Dedicated
	bgmusic/20 Hilarious Jokes	Catherine Michael	20 Hilarious Jokes
	Conmigo Pachanga	Eddie Palmieri	Sugar Daddy
	Ritmo Caliente	Eddie Palmieri	Sugar Daddy
	Halo	Michael Salvatori	Halo: Original Soundtrack
Low groove	Primavera	Ludovico Einaudi	Divernire
	FL Studio—Acoustic Guitar, Violin	Farhan Khan	N/A (Single)
	Druid Fluid	Yo-Yo Ma, Edgar Meyer	Appalachia Waltz
	Bryter Layter	Nick Drake	Bryter Layter
	Farewell	Apocalyptica	Apocalyptica

Supplementary analyses

Effect of instructions to synchronise to music

Previously, we found that instructions to synchronise gait to music elicited slower, shorter, and more variable strides (Leow et al. 2018). To test if this replicated in this dataset, we compared conditions with/without instructions to synchronise, using a Synchronise (Synchronise, Freely walk) x Groove (Low Groove, High Groove) x Beat Salience (No Met Embedded, Met Embedded) ANOVA with between-subjects factors Age (Young, Older) and BP Ability (Weak Beat-perceivers, Strong Beat-perceivers) on gait parameters. We focussed here on the effect of synchronisation.

Gait speed parameters

When not instructed to synchronise to the beat (i.e., freely walking conditions), participants walked faster, taking more steps and longer strides, than in the synchronise conditions (see Fig. 1), as shown by significant main effects of synchronisation for stride velocity [$F(1, 34) = 12.45$, $p = 0.001$, partial η-squared = 0.27], stride time [$F(1, 34) = 4.85$, $p = 0.03$, partial η-squared = 0.12], and stride length [$F(1, 34) = 13.96$, $p < 0.001$, partial η- squared = 0.29]. Instructions to synchronise slowed strides in both strong and weak beat-perceivers, but more so in weak beat-perceivers, as shown by an Synchronise x BP Ability interaction for stride velocity [F(1, 34) = 4.90, p = 0.03, partial η-squared = 0.13] and stride time [F(1, 34) = 8.00, p = 0.008, partial η-squared = 0.19]. Gait was slowest when weak beat-perceivers were synchronizing to low-groove music, as shown by a significant Groove x Synchronise x BP Ability interaction for stride velocity [F(1, 34) = 6.89, p = 0.013, partial η-squared = 0.17] and stride time [F(1, 34) = 5.66, p = 0.02, partial η-squared = 0.14].

Gait variability

Stride velocity and stride length were more variable when instructed to synchronise to the beat than when freely walking with music (see Fig. 1), as shown by main effects of synchronisation for stride velocity variability [F(1,34) = 21.82, p < 0.01, partial η-squared = 0.39], stride length variability [F(1,34) = 37.01, p < 0.01, partial η-squared = 0.52]. The main effect for stride time variability missed significance [F(1,34) = 3.43, p = 0.07, partial η-squared = 0.09].

Bias for stability

Instructions to synchronise increased the bias for stability (see Fig. 2), as shown by main effects of synchronisation on stride width [F(1,34) = 10.93, p = 0.002, partial η-squared = 0.24], and double support time [F(1,34) = 4.48, p = 0.042, partial η-squared = 0.12]. For stride width, negative effects of synchronizing were most prominent with low-groove music, as shown by a significant Groove x Synchronise interaction [F(1, 34) = 4.29 p = 0.046, partial η-squared = 0.11], as instructions to synchronise increased stride width to a greater extent with low-groove music (0.157 [− 0.271, − 0.044], t = − 3.832, pbonf = 0.002), than with high-groove music (mean difference between freely walking and synchronise conditions = − 0.096 [− 0.209, 0.018], t = − 2.33, pbonf = 0.107).

In summary, when walking with music, instructions to synchronise elicited slower, shorter, and more variable strides than walking without instructions to synchronise.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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