



Walking on music

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Abstract

The present study focuses on the intricate relationship between human body movement and music, in particular on how music may influence the way humans walk. In an experiment, participants were asked to synchronize their walking tempo with the tempo of musical and metronome stimuli. The walking tempo and walking speed were measured. The tempi of the stimuli varied between 50 and 190 beats per minute. The data revealed that people walk faster on music than on metronome stimuli and that walking on music can be modeled as a resonance phenomenon that is related to the perceptual resonance phenomenon as described by Van Noorden and Moelants (Van Noorden, L., & Moelants, D. (1999). Resonance in the perception of musical pulse. *Journal of New Music Research*, 28, 43–66).

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1. Introduction

There is a close relationship between music and body movement. In order to sing, blow the flute, strike the violin or hit the drum, one needs a moving body that performs the sound producing action. Also listening to music is often accompanied by body movements. Just think about dancing or clapping hands during a live pop concert. Several sports activities, like aerobics or spinning, are based on the use of music. Soldiers walk

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on the beat of military marches and people performing physical and often repetitive tasks sing work songs to synchronize their physical movements (Mc Neill, 1995). The relation between music and body movement is stressed in current theories on embodied cognition where the role of the body is seen as a mediator for music perception (Leman, 2007). Next to a theoretical approach, moving on music should be studied in an experimental way. In this article two aspects of moving on music, synchronization and spatialization, are studied experimentally.

The synchronization of body movements with music has been studied extensively in tapping experiments (Large, 2000; Repp, 2006). In these experiments people have to tap along with the perceived musical tempo. Several aspects of musical synchronization have been observed and quantified. They include the negative asynchrony (i.e., the phenomenon that during tapping in synchrony with an auditory metronome the taps tend to precede the tones by a few tens of milliseconds), variability, and rate limits (see Desain & Windsor, 2000; Repp, 2006). Another aspect of musical synchronization is concerned with the metrical level at which people tend to synchronize their taps. For example, one can synchronize with a musical tempo of 120 beats per minute (BPM), but also with half (60 BPM) or twice this tempo (240 BPM). Several studies have shown that people prefer to tap with a tempo that is close to a neutral or spontaneous tempo, which is associated with natural types of body movement (e.g., Fraisse, 1982; Van Noorden & Moelants, 1999). Also in music theory (e.g., Willemze, 1956) it has been observed that the moderate musical tempi (cf. *andante*) are close to some biological rhythms of the human body such as the heart-beat and the tempo of walking. Based on an overview of different experiments, Moelants (2002) concluded that there is a clear correspondence between the tempi of spontaneous movements, as observed in walking, clapping and finger tapping, and tempi perceived in music.

While many studies have focused on the synchronization aspect, much less attention has been paid to what is called here the spatialization aspect. This aspect refers to the spatial movement trajectories of human body parts between successive synchronization points. It is plausible to assume that the spatial trajectories of repetitive body movements may vary a lot, depending on the character of the music. This might be independent of the musical tempo. Clynes (1977, 1995) was interested in the temporal forms of emotions and asked participants to press a continuous pressure sensitive button in a repetitive way while listening to music. Becking (1958) connected two-dimensional shapes to the musical beat by observing his own conducting-like movements. These authors stressed that moving the body on music is not only a matter of synchronizing with fixed points in time, but also of making a connection between these points.

In order to study both the synchronization and the spatialization aspect of moving on music, we focused on a basic movement pattern that nearly all humans perform in daily life, namely walking. The choice to study walking movements was inspired by the work of MacDougall and Moore (2005). They determined the long-term energy spectrum of motor activity and found a highly tuned resonance frequency at 2 Hz due to human locomotion. No influences of the mechanical properties of the body on this movement spectrum were found. This poses an enigma for investigators of human walking as many studies have linked the preferred walking tempo to the mechanical properties of the body (e.g., Bertram, 2005). Furthermore, the authors argued that the spontaneous movement spectrum shows a strong resemblance with the histogram of musical tempi as described by Moelants (2002). Van Noorden and Moelants (1999) have shown a strong link

between the histogram of musical tempi and a perceptual resonance curve with a resonance frequency at 2 Hz. Several phenomena in rhythm perception and production, such as subjective rhythmization, the existence region of musical pulse, tapping tendencies along polyrhythms and peaks in tempi histograms of musical pieces, can be explained on the basis of this resonance model. An interesting question is whether this perceptual resonance curve is linked to the global locomotor resonance curve as found by MacDougall and Moore, and also whether it is independent of the mechanical properties of the body.

In music science, some studies have focused on music and walking. However, none of these studies have focused on the basic link between walking tempo, walking speed, and musical tempo. In an experiment by Friberg, Sundberg, and Frydén (2000), sonifications of different gaits were made by mapping the force curve of different kinds of walking to the sound level envelope for a single tone of 196 Hz. These sonifications were then used in three different listening experiments. The aim was to see whether the motion quality of different gaits could be transferred to music and perceived by the listeners. The authors' conclusion was that the motion character of a gait can be conveyed to a listener by the sound level envelopes of tones, modeled from the vertical pattern exerted by the foot. In another study, Friberg and Sundberg (1999) observed that the average velocity curve of runners coming to a stop fitted well with the average tempo curve of the final *ritardando* in recordings of baroque music. This study fits well into a series of studies proposing kinematic models for the final retard as well as for *ritardandi* and *accelerandi* from complete performances (Honing, 2003; Todd, 1992a, 1992b). Giordano and Bresin (2006) investigated the hypothesis that similarities between music performance and locomotion are possible because expression of emotions in music originates, at least in part, as an allusion to locomotion sounds. They tested this view by studying human locomotion sounds in both production and perception.

In the field of movement science, we are not aware of any study that addresses the specific relation between music and walking. In their review article on the psychophysical effects of music in sport and exercise, Karageorghis and Terry (1997) concluded that the synchronization of submaximal exercise (i.e., exercise below maximum effort) with musical accompaniment results in an increased work output. Music apparently reduces the rate of perceived exertion during submaximal exercise and tends to enhance the affective states at both medium and high-level work intensity. The effect of asynchronous music (background music) in contributing to optimal arousal was found to be unclear.

In the present article we study whether people can synchronize their walking movements with the musical tempo and whether their walking tempo corresponds with their tapping tempo on the same music. Next, we study, independently of the musical tempo, the spatialization of the walking movements in terms of walking speed or step size.¹ We assume that the musical character may influence the step size (and thus the walking speed) of the walking movements. We study both the spatialization differences between walking movements on musical and metronome stimuli of the same tempo and between walking movements on different musical stimuli of the same tempo. Finally, we investigate whether the spatialization of the movements shows the resonance phenomenon as postulated for music perception.

¹ See Appendix 1 for an overview of the relevant terms used in the article.

2. Experiment

2.1. Participants

Twenty healthy persons (10 men, 10 women) participated in the experiment, ranging in age from 20 to 29 with an average of 25 years. Seventeen participants played a musical instrument (on average 5.9 h per week); four of them were professional musicians. They received a gift coupon for their participation.

2.2. Procedure

For the first part of the experiment, the participants were invited to the open-air athletics track of Ghent University. They were verbally instructed about the experimental task. Participants had to walk while listening to two different series of musical fragments. Each series took 45 min and consisted of 34 musical fragments with a length of 1 min and six metronome fragments with a length of 30 s. Between each fragment a 5-s pause was inserted. Participants were explicitly instructed to synchronize their walking tempo with the perceived musical pulse, that is, with the first spontaneously perceived tempo. Even if the first felt tempo was very fast or very slow, they had to try to maintain this tempo in a walking way and were not allowed to run. The music was played with an mp3 player (Samsung YP-F1) and headphones (Sennheiser HD 62 TV). Walking tempo was measured by putting a small mp3 recorder (Samsung YP-F1, weight: 30 g) on one of the participants' shoes and recording the sound of the footsteps in wave format (8000 Hz, 16 bit, mono). Walking speed was measured with a GPS device (Garmin Forerunner 305, GPS velocity inaccuracy <0.05 m/s). The sample frequency of the GPS device was 1 Hz. During the entire experiment, heart rate was measured with the heart rate monitoring function of the GPS device. At the beginning of each session the experiment instructor activated the GPS, mp3 player and mp3 recorder. Participants were instructed to start walking as soon as they heard the first musical fragment. At the end of each fragment they had to stand still and push the lap button on the GPS device. They had to walk further as soon as the next fragment started. The experiments took place under good weather conditions with a clear sky. There was a short break between the two series of musical fragments in which some drinks and fruits were provided.

For the second part of the experiment, the participants were invited to the department of Musicology at Ghent University. The experimental task here was to listen to the same 68 musical fragments as in the walking part and to tap along with the perceived musical pulse. The tapping data were collected with a computer program (developed in the Pure Data graphical programming environment, <http://puredata.info/>) specifically designed for this purpose. The tap moments were entered by pressing a key at the perceived rate. After each fragment, participants had to give subjective ratings on whether they found the music: easy or difficult to tap along with, familiar or unfamiliar, good or bad (referring to their personal feeling about the music), fast or slow, happy or sad, inducing lots of movement or static, angular or fluent, loud or quiet. Ratings were made by putting a vertical line on a 10 cm horizontal bar with at both ends of the bar one of the two bipolar adjectives.² At the end of the experiment participants received a gift voucher of 10€ for a well-known CD store

² These subjective data will not be analyzed in the current article.

for their participation in both parts of the experiment. Additionally, basic information of the participants (age, musical experience, musical preference, and so on) was gathered, as well as their body length and weight, leg length, and hip width.

2.3. Stimuli

The set of musical stimuli was balanced on tempo. The tempo ranged from 50 BPM to 190 BPM. From 50 BPM to 160 BPM, for every successive 4 BPM two musical fragments were selected (two musical fragments with tempo 50 BPM, 54 BPM, 58 BPM, and so on). From 160 BPM to 190 BPM, every 5 BPM two musical fragments were selected. This division resulted in a total of 68 musical fragments.³ The tempi of the musical fragments were determined by using Jackson (<http://vanaeken.com/>), a DJ software packet that allows determining the tempo of a musical piece both in a visual and auditory way. As the determination of the musical tempo is always ambiguous (cf. *Mc Kinney & Moelants, 2007*), three musical experts (musicologists with experience in music perception experiments) determined the tempo. Only those fragments for which all three experts agreed upon the musical tempo were selected. The tempi as determined by the experts were called the ‘nominal tempi’. The tempi of the metronome stimuli also ranged from 50 BPM to 190 BPM. Starting with 50 BPM, every 12 BPM a metronome stimulus was made. This resulted in a total of 12 metronome stimuli. The musical fragments together with the metronome fragments resulted in a total of 80 stimuli. These 80 stimuli were divided over two stimuli series. The order of the stimuli was randomized in such a way that four subranges of the whole tempo range appeared in a balanced way across the session. In total four different orders were constructed. Each participant received one of the four randomized orders. All orders occurred equally often. The musical fragments were taken from a wide variety of musical styles: rock, pop, techno, dance, trance, hard rock, film music, world music, et cetera. Each musical fragment had a duration of 1 minute. These fragments were selected from the original full songs. The criteria for these selections were a stable tempo and a musical character that stayed constant during a timespan of 1 min. The fragments were cut out of the original songs with a sound editor. Fade in and fade out (10 ms) were placed at the beginning and end of each fragment. At the end of each fragment a 5-s pause was added. The amplitude of all musical fragments was normalized. The metronome fragments were made with the modular software synthesizer Analog Box (<http://www.andyware.com/abox2/>). Each metronome fragment had a total duration of 30 s. A 5-s pause was added at the end of each metronome fragment.

In the second part of the experiment (tapping task) the stimuli were the same 68 musical fragments as used in the walking experiment. Since previous experiments showed that 30 s was sufficient to record the tempo of tapping (cf. *Mc Kinney & Moelants, 2007*), the duration of each fragment was reduced to half a minute, which allowed shortening the length of the experiment. The metronome stimuli were not used during this part of the experiment.

2.4. Analysis

Concerning the walking task, the GPS device’s software (Garmin Training Centre, <http://www.garmin.com/products/trainingcenter>) calculated the mean walking speed for

³ The list of musical stimuli can be obtained from the authors, on request.

each walking lap. The walking tempo was obtained by analyzing the sound recordings of the footsteps of the participants. This was done manually by the experimenter by tapping along with the footstep recordings using the tap function of the software tool *jtick* (<http://sourceforge.net/projects/jtick>). This tap function gives an estimate of the tapped tempo, and thus in this case of the walking tempo. Concerning the tapping task, the tap tempi were calculated automatically (by the Pure Data computer program also used for capturing the tapping data) based on the time duration between the tapping moments. The resulting data (walking speeds, walking tempi and tap tempi) were gathered in an Excel data sheet. For each walking tempo and tapping tempo a label was provided, representing the metrical level (relative to the nominal tempo) at which participants synchronized their walking tempo (1 = synchronizing with the nominal tempo, 2 = synchronizing with the double of the nominal tempo, 0.5 = synchronizing with the half of the nominal tempo, 0.25 = synchronizing with a quarter of the nominal tempo, 0 = not synchronized). The data were analyzed using the statistical software packet SPSS (<http://www.spss.com>).

3. Results

First, we examined the walking speed and tempo while synchronizing with the perceived musical pulse. In particular, we compared the degree of synchronization and the metrical level at which the participants walked with the degree of synchronization and the metrical level at which the participants tapped on the same music. Next, we examined differences in walking speed (spatialization) while synchronizing with music and with simple metronome stimuli and tested the basic assumption that music can influence walking speed, independently of musical tempo. Finally, we analyzed the step size as a function of the walking tempo for each participant individually, and approached the spatialization aspect in terms of the resonance phenomenon that was found to play a role in music perception (Van Noorden & Moelants, 1999).

3.1. Synchronization with the music in walking and tapping

In the majority of the cases (72.6%) the walking tempo was equal (approximately within ± 1 BPM) to the nominal tempo (see the thick principal diagonal in Fig. 1). In 10.1% of all cases participants stepped at half the nominal tempo, which occurred more frequently towards the higher nominal tempi (see the lighter diagonal below the principal diagonal in Fig. 1). There were also participants who stepped on the double tempo (3.2%), primarily in the range of slow nominal tempi (the partial diagonal above the principal diagonal in Fig. 1). Finally, there were some participants (mainly participants 8 and 18) for whom the walking tempo was only equal to the nominal tempo in the region of 120 BPM. Above and below this tempo they did not synchronize with the music, but still there seemed to be an influence of the nominal tempo since their walking tempo increased slightly as the nominal tempo increased. In one exceptional case (participant 10), very slow walking tempi (sometimes at a quarter of the nominal tempo (0.4%)) were observed. In 13.9% of all cases the walking tempo was not synchronized with the stimuli at all. If we excluded the metronome stimuli from this analysis slightly different percentages were obtained: 69.8% of all cases were synchronized with the nominal tempo, 11.2% with the half, 3.6% with the double, and 0.3% with the quarter, whereas 15.1% of all cases were not synchronized. Considering only the metronome stimuli resulted in the following

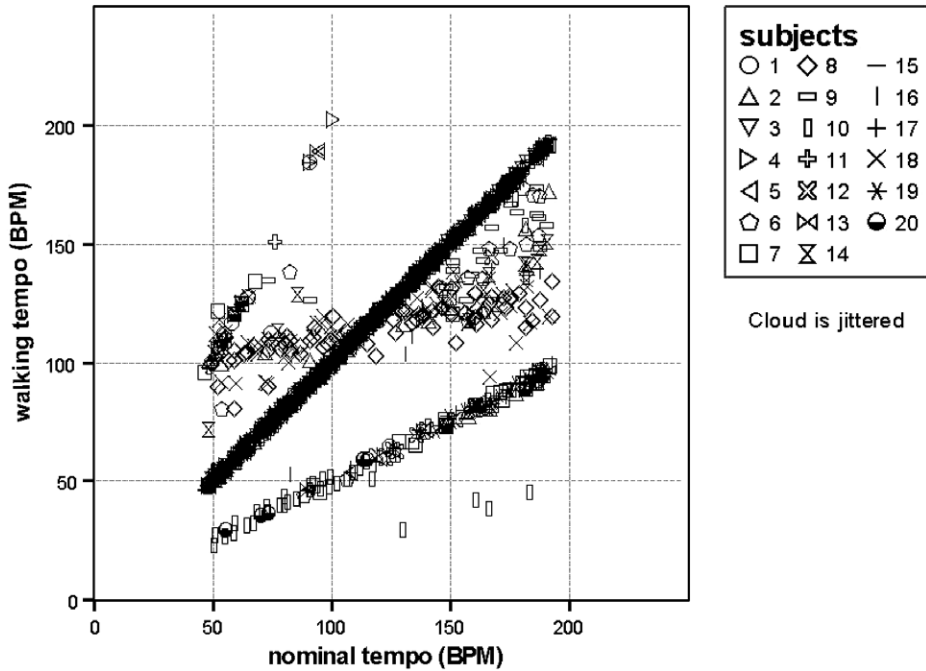


Fig. 1. Walking tempo (BPM) as a function of the nominal tempo (BPM) of 20 participants.

percentages: 88.8% of all cases was synchronized with the nominal tempo, 3.8% with the half, 0.8% with the double, and 6.7% was not synchronized. See Table 1 for an overview of the different synchronization percentages.

If we look at the number of cases for each nominal tempo in which participants did not synchronize with the musical stimuli (at the nominal tempo, or an other metrical level), as displayed in Fig. 2, we can distinguish a region between 106 and 130 BPM where there were less cases in which participants did not synchronize with the music. We could say that an optimal walking tempo appeared to exist around 120 BPM. This is consistent with previous findings on spontaneous tempo (Moelants, 2002).

Fig. 3 shows the relationship between tapping tempo and nominal tempo. In most cases of the tapping experiment participants tapped at the nominal tempo (84.4%). There were fewer participants who tapped at half the nominal tempo (6.5%) than in the walking condition and there seemed to be less tendency to do this primarily at fast nominal tempi. The

Table 1

Overview of the synchronization percentages at the different metrical levels for all stimuli, the musical stimuli only, and the metronome stimuli only

	Metrical level (%)				
	0	0.25	0.5	1	2
All stimuli	13.90	0.30	10.10	72.60	3.20
Musical stimuli only	15.10	0.30	11.20	69.80	3.60
Metronome stimuli only	6.70	–	3.80	88.80	0.80

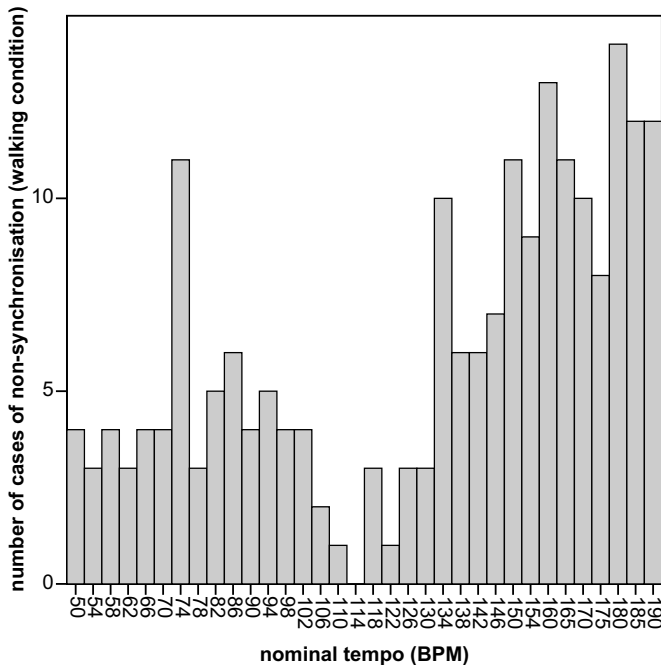


Fig. 2. Number of cases of non-synchronization with the musical stimuli (in the walking condition) for each nominal tempo (BPM).

tendency to tap at the double tempo at lower nominal rates was more or less the same (5.1%). In 0.1% of the cases participants tapped at a quarter of the nominal tempo. Only one participant (8) was unable to synchronize in the tapping condition. This was one of the two participants who did not synchronize during the walking part as well. In total, 3.6% of all cases were not synchronized.

A comparison of the walking data with the tapping data revealed that in most cases (80.7%) participants tapped at the same rate as they walked. In 12.9% of all cases the walking tempi were at half the tapping tempi, in 0.8% at a quarter, in 5.4% at the double and in 0.2% at the quadruple.

3.2. Walking speed as function of walking tempo

The following analysis only took into consideration those walking speeds and tempi that were the result of a synchronization of the participant's walking movements with the nominal tempo as put forward by the experts (72.6% of all cases). Data that were the result of a walking tempo synchronized at a different metrical level were excluded from the analysis. This restriction allowed comparisons between the spatialization aspect (walking speed) of walking movements on musical stimuli with the same nominal and walking tempo, as well as between the spatialization of walking movements on musical and metronome stimuli with the same nominal and walking tempo.

The tempo/speed curve depicted in Fig. 4 shows a linear character from 50 to 114 BPM. From 118 to 190 BPM the walking speed appeared to stabilize. The maximum walking

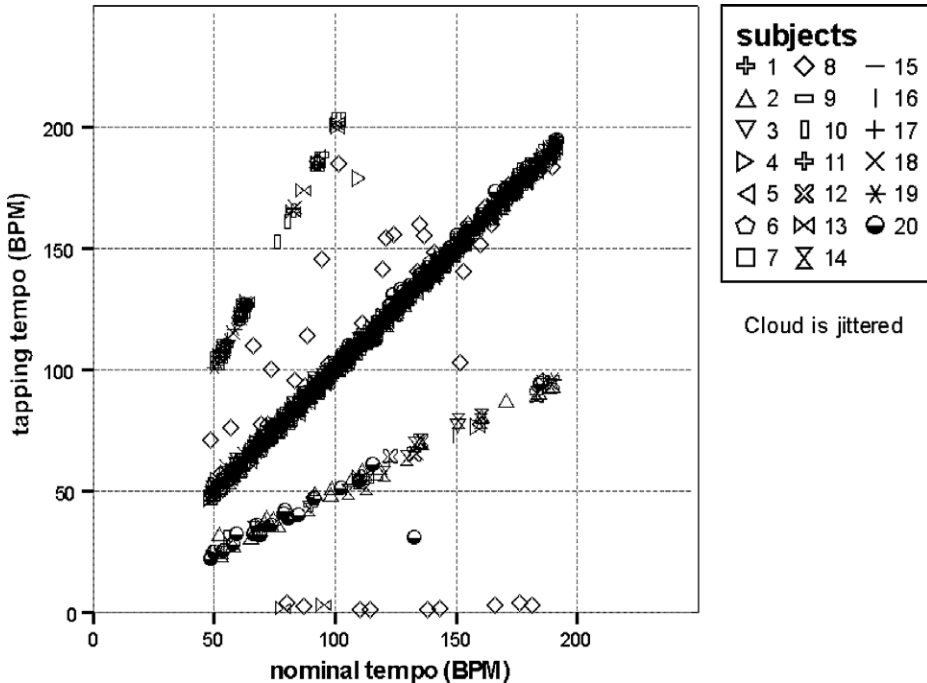


Fig. 3. Tapping tempo (BPM) as a function of the nominal tempo (BPM) of 20 participants (the tapping rate was set to zero for the cases in which it was impossible to determine the tapping tempo by the experimenter).

speed occurred somewhere between a walking tempo of 126 and 142 BPM. Walking at a higher tempo did not result in an increasing walking speed. The variances of the different walking tempi were unequal (Modified Levene test, $p < .01$). The lowest variance (0.106) was found at synchronizing with the musical piece of 50 BPM. The highest variance (3.254) was found at synchronizing with the musical piece of 190 BPM. No differences were found between men and women.

Walking has strong roots in the biomechanics of the human body. We may wonder whether music can possibly influence such a basic motor activity. Therefore, we verified to what extent the music had an impact on the speed/tempo relationship as shown in Fig. 4. This question was answered by looking at the differences between the walking curve while synchronizing with music and the walking curve while synchronizing with simple metronome stimuli. An independent t test for equal variances indicated that over all tempi the walking speed on the metronome stimuli was significantly lower than on the musical stimuli, $t(1160) = 3.929$, $p < .01$ (an alpha level of .05 was used, two-tailed test). Thus, the music made people walk faster. Again, we observed a gradual increase of variance for an increase of walking tempo for both the walking speeds on the metronome stimuli and the musical stimuli. Statistical tests however did not reveal any significant differences in variance between the music and metronome condition. No significant differences were found between men and women.

The next question was whether there was, in addition to the difference in walking speed between musical stimuli and metronome stimuli of the same nominal tempo, also a difference between the two musical stimuli of the same nominal tempo. This was, however, not

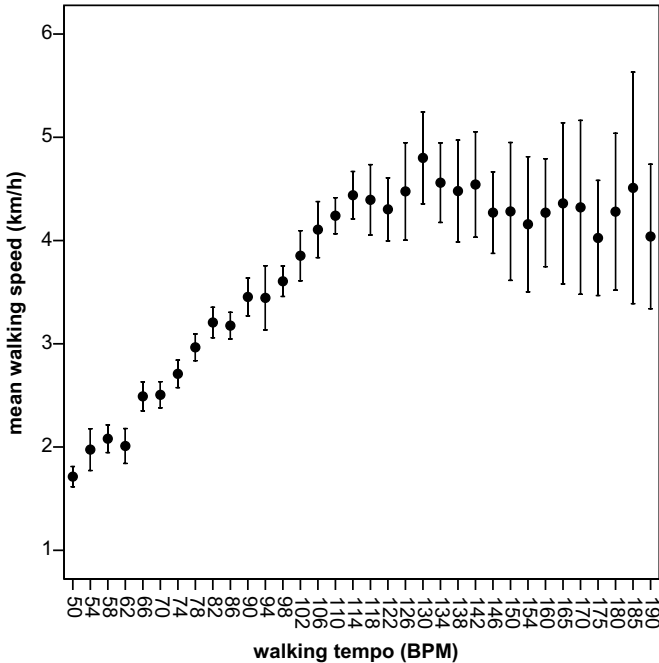


Fig. 4. Mean walking speed (km/h) with 95% confidence interval as a function of walking tempo (BPM).

confirmed by the data. No statistical differences in walking speed were found between two musical pieces of the same tempo. The variability between participants was much greater than the variability between pieces.

3.3. Step size as function of the walking tempo

Fig. 5 shows the step size as a function of walking tempo for each participant individually. All data are included, regardless of whether the participants synchronized with the nominal tempo, with another metrical level, or did not synchronize at all. The step size was obtained by dividing walking speed by walking tempo. There were some participants (8, 16, 18 and 19) who showed only a limited range of walking tempi. Most other participants made large steps in the middle of the range and smaller steps towards the slower and faster walking tempi. Some participants had a more or less constant step size at the slow temp- end (e.g., participants 1, 10 and 11). A distinction could be made as to how the step size decreased towards the fast walking tempo: either gradually following a continuous curve (e.g., participant 17) or in a discontinuous way, with a sudden jump towards smaller step sizes at faster walking tempi (e.g., participants 4 and 15). A comparable dichotomy was recently observed by [Bertram \(2005\)](#). In a walking condition where step frequency was constrained two behavioral strategies were observed, one that fitted a higher speed optimization and one that fitted a lower speed optimization.

Different factors could have influenced step size. The first that come to mind are leg length, body length, body weight, and gender. One additional factor should be considered,

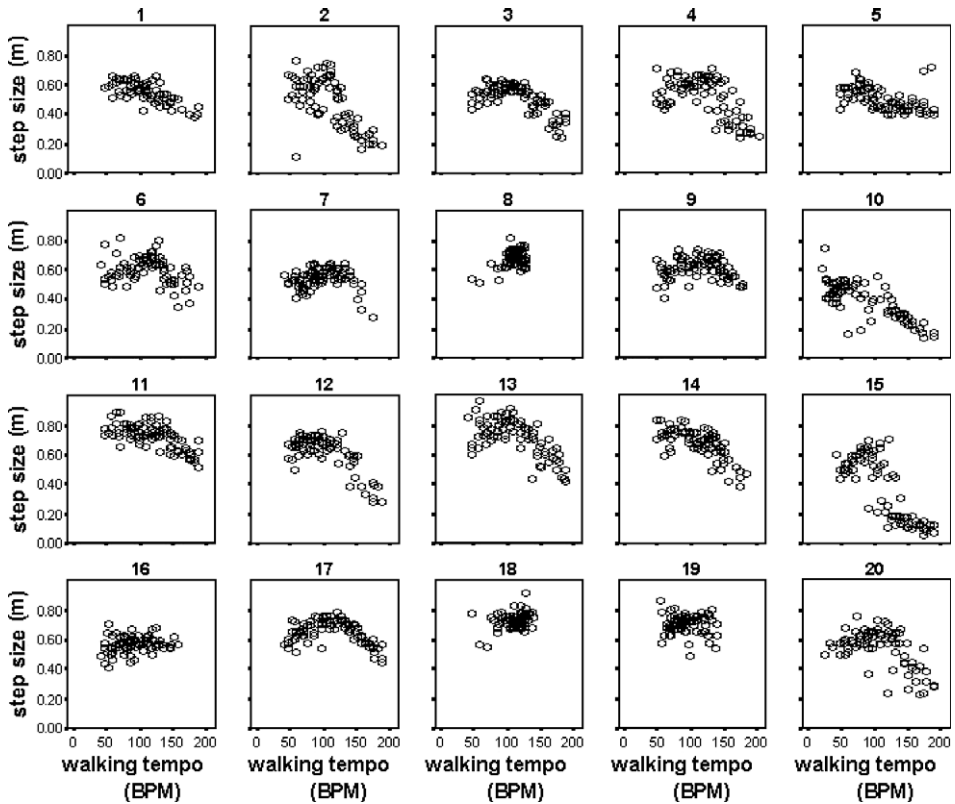


Fig. 5. Step size (m) as function of walking tempo (BPM) of the 20 participants.

namely, the effort that participants put into the walking task. People can interpret this walking task in different ways. On the one hand, it can be interpreted as a physical exercise with a focus on making large steps. On the other hand, it can be interpreted as a kind of dancing with a focus on the synchronization of the movements with the music, without putting much physical effort in the exercise. The most important reason to register heart rate was to check whether the physical effort that participants invested in the task was more or less equal during the session. A regression analysis with step size as dependent variable and leg length, body length, weight, gender, heart rate, hip width, and age as independent variables was performed. Two participants were left out of the analysis: participant 15 because of the break in the step size as function of walking tempo and participant 13 because of an atypical heart rate reading. Due to the nonlinear behavior of step size versus walking tempo, the walking tempo was also incorporated as a squared variable. From this analysis it appeared that beyond walking tempo, both linearly and squared, leg length was the only variable that gave a substantial contribution to the explanation of the variance in the data (coefficients: walking tempo (squared): -0.003 ($t = -18.5$, $p < .001$), walking tempo (linear): 0.007 ($t = 15.8$, $p < .001$), leg length: 0.005 ($t = 11.0$, $p < .001$)). This regression explained 33% of the variance. See Fig. 6 for the results.

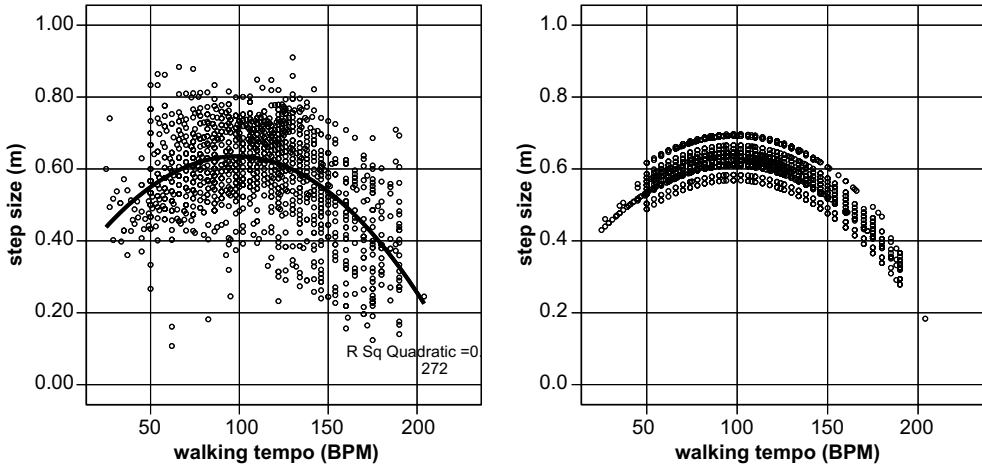


Fig. 6. Regression results of step size (m) versus walking tempo (BPM). Left: data of 18 participants with quadratic trend line. Right: results of regression model including influence of leg length.

3.4. Resonance in locomotion versus perceptual resonance

The curved relationship between step size and walking tempo as shown in Fig. 6 suggests that a resonance phenomenon underlies this relationship. Resonance can be described as the increase in amplitude of oscillation in a physical system exposed to a periodic external force when the driving frequency (or one of its components) approaches the frequency where it vibrates most easily. Eq. (3.4.1) describes the relative amplitude (A) of the linear harmonic oscillator as a function of the frequency of the external force (f_{ext}). It is characterized by two parameters: the resonance frequency of the oscillator (f_0) and the damping constant (β) (Kneubühl, 1997)

$$A = \frac{1}{\sqrt{(f_0^2 - f_{\text{ext}}^2)^2 + \beta f_{\text{ext}}^2}} \quad (3.4.1)$$

In Van Noorden and Moelants (1999) a perceptual resonance curve was defined, which provided a useful model to explain existing experimental data on perceptual grouping and tapping along isochronous and polyrhythmic tone sequences. This curve was derived from a harmonic oscillator by subtracting the critically damped resonance curve (second term in (3.4.2)) from the resonance curve (the first term in (3.4.2)) at the same f_0 . The resulting resonance curve was called the ‘effective resonance’, that is, the extra amplitude one feels due to resonance beyond the movement at critical damping, which is a ‘passive’ result of the external force

$$A = \frac{1}{\sqrt{(f_0^2 - f_{\text{ext}}^2)^2 + \beta f_{\text{ext}}^2}} - \frac{1}{\sqrt{f_0^4 - f_{\text{ext}}^4}} \quad (3.4.2)$$

Walking on music is in a way very similar to tapping on music. Instead of tapping with the hand on the pulse of the music one does it with the feet. Possibly the perceptual resonance phenomenon also plays a role in walking on music or is in fact closely related to the loco-

motion resonance. Viewing the locomotion system as a resonance system is not new. Many authors have shown for instance that the preferred period of walking is closely related to the period of a swinging pendulum (e.g., Holt, Hamill, & Andres, 1990). A smooth curve like the trend line in Fig. 6 could easily be interpreted as a typical resonance curve. However, also the curves with the two disjunctive step sizes (e.g., participant 15, see Fig. 5) could be interpreted as representing a resonance phenomenon, albeit a nonlinear one. If a resonator is nonlinear in the sense that the resonance frequency increases with increasing amplitude, then the phenomenon of ‘resonance fold-over’ may appear and show this sudden amplitude jump (see Kneubühl, 1997, p. 136). We limited ourselves, however, to an analysis based on the simpler linear model.

To compare the walking data with the resonance curve of the perceptual phenomena (Van Noorden & Moelants, 1999) the resonance curve of a linear harmonic oscillator was fitted to the data of the 16 participants that did not show the breaking up of the resonance curve. As we are considering now real amplitudes we deal with real resonance curves and not with ‘effective’ resonance curves as in the perceptual case. Amplitude a , resonance frequency f_0 , and damping factor β are the three parameters that have been used for fitting the model to the data (3.4.3)

$$A = \frac{a}{\sqrt{(f_0^2 - f_{\text{ext}}^2)^2 + \beta f_{\text{ext}}^2}} \quad (3.4.3)$$

First a single value for the resonance frequency f_0 and a single value for the damping factor β were obtained (i.e., the location and the width of the resonance) for all 16 participants. The mean value for f_0 was 147.1 steps per minute and the mean value for the damping factor was 0.97. Second, the amplitude a of the resonance curve was estimated as a linear function of the leg length, the weight and heart rate of the participants. At the same time, small individual correction factors for the f_0 value were estimated for each participant. These individual correction factors for the f_0 had an average of 1 BPM and a standard deviation of 8 BPM. This two-step approach for finding f_0 was chosen in order to find stable solver solutions while using a minimum number of adjustable parameters. The fit of the model explained 84% of the variance of the data of the 16 participants used for the model estimation. The f_0 values seemed to be marginally correlated to the leg length and body weight. However, experiments with more participants are needed to confirm this.

The resonance curve for walking on music had a higher f_0 value and a stronger damping factor than the resonance curve for perceptual phenomena as found by Van Noorden and Moelants (1999) (see Fig. 7). The perceptual resonance curve decreased more rapidly to zero at the slow tempo side than the locomotion curve due to the fact that the locomotion curve is a real resonance curve. The f_0 of the locomotion resonance curve was close to 150 BPM while the f_0 value for the perceptual resonance curve was close to 125 BPM. But due to the difference in damping the tops of the resonance curves are in both cases near 120 BPM (with increasing damping values the frequency of the maximum amplitude is deviating more and more from the f_0 value (see Kneubühl, 1997)).⁴ The perceptual resonance seems to be tuned to the most efficient region of the locomotion resonance peak. It

⁴ A comparison of the fits obtained by quadratic curves, as applied in Fig. 6, and a fit with a resonance curve learns that the highest value of the curve is located at a slightly higher frequency in the latter case (ca. 100 vs 120 BPM).

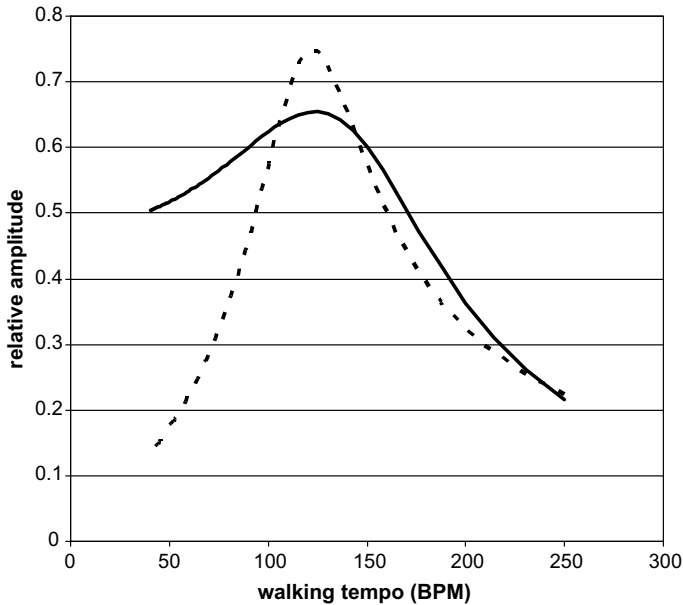


Fig. 7. Comparison of locomotion (full line) and perceptual (dashed line) resonance curves.

appeared that the resonance frequency was determined by the mechanical properties of the body, like leg length, but that the control mechanism could regulate damping and stiffness in such a way that the maximum amplitude was always near 120 BPM. The central control mechanism seems to be tuned to this most efficient frequency for locomotion.

4. Discussion

Both in the walking and tapping part of the experiment, most participants synchronized with the musical and metronome stimuli. The two participants (8 and 18) who only synchronized their walking tempo properly around 120 BPM are interesting because in the data of these participants we still could observe an increasing walking speed as the nominal tempo increased. This implies that, although these participants did not know how to synchronize, the music still had a significant impact on their walking tempo. We assume that they experienced the music as background music, rather than a signal to synchronize with. It appears then that music as a background phenomenon can influence a basic bodily activity in an unconscious way. The observation that the tempo of background music can influence different kinds of human activity was already made by several authors. For example, [Milliman \(1986\)](#) demonstrated that the tempo of background music can significantly affect the behavior of restaurant costumers and [Kallinen \(2002\)](#) showed that the musical tempo has a clear effect on reading news from a pocket computer.

We limited the analysis to a comparison of the tempo of walking and tapping with the tempo of the music. We did not (yet) look at the precise synchronization of the steps/taps with specific events in the music such as, e.g., the synchronization of the step with the occurrence of a rim shot or a bass sound. Also the corrections to misalignments between

the steps and the musical events were not studied. Such an investigation would be of great interest, particularly in the context of the resonance theory where one expects changes in the phase relationship between driver and driven object while shifting from low to high frequencies, going through the resonance frequency.

The comparison between the walking data while synchronizing with music and while synchronizing with simple metronome stimuli indicated that the walking tempo/speed relationship was clearly influenced by music. It seems reasonable to assume that the overall shape of the curve was due to the physics of human walking, but that the walking speed was consistently slightly increased over a broad range of tempi under the influence of music. Music makes people walk faster and therefore might be used to stimulate movement. In their review article [Karageorghis and Terry \(1997\)](#) concluded that the synchronization of submaximal exercise (exercise below maximum effort) with musical accompaniment results in an increased work output. We showed that a similar increased work output exists in an exercise condition like walking.

The hypothesis put forward in the introduction, namely that different musical pieces may differ in power to influence walking speed independently of musical tempo, was not confirmed by the data. In other words, differences in spatialization were distinguished between metronome and musical stimuli, but not between musical stimuli of the same tempo. A first explanation for this is that walking speed may not be the most appropriate variable to study the spatialization aspect of moving on music. We think that the total energy that participants want to express by their walking may not be entirely readable in the walking speed, but also in variables like the force with which one puts his foot down, the movement of the arms, or the vertical movement of the legs. A second explanation is that only two musical pieces of the same tempo might not reveal any significant difference. Therefore, further research should focus on a wider variety of musical fragments of the same tempo in order to determine the precise aspects of music, besides the musical tempo, that might influence the spatialization of body movements. We think that such aspects do exist as there is a clear difference between musical stimuli and metronome stimuli and metronome stimuli could be interpreted as the most rudimental form of music. Some examples of such aspects might be the amount of energy, number of musical events, or number of musicians. Musical energy, loudness or the impression that some instruments are played with more energy than others may evoke more energy in the listener's movement behavior. More events per musical beat may increase the feeling of more speed, and the amount of musicians may increase the feeling of belongingness to the group and enhance the enthusiasm of the listener ([Mc Neill, 1995](#)). This could be studied in a more probing manner, for example by asking people to walk on different musical pieces judged to have different degrees of 'groove' ([Madison, 2007](#)).

An important feature of the present study was the analysis of the spatialization aspect of walking on music in terms of a resonance phenomenon. We showed that the spatialization of walking movements on music is characterized by a similar resonance phenomenon (with an f_0 near 120 BPM) as used to explain the results of tapping experiments ([Van Noorden & Moelants, 1999](#)). As the biomechanical properties of the hand and lower arm (used in tapping) are quite different from those of the locomotion system the question arises: what is the nature of the resonating system? The close correspondence between the resonance of the locomotion system and the histogram of musical tempi ([MacDougall & Moore, 2005](#)) makes us suppose that the perception of musical pulse is due to an internalized model of the locomotion system, i.e., we feel how we can move (dance) on a piece of

music. The question remains whether this internalized model is in terms of one's own body mechanics or in terms of a more generalized, perhaps culturally determined, model. A pointer into the direction of a more generalized model is the fact that MacDougall and Moore (2005) did not find any significant influence of the mechanical properties of the body such as total body length, leg length and body mass index on the long-term movement spectrum. This is quite a daring speculation as it means that even the unconscious control of movement is made according to this generalized model and not to one's own biomechanics. In any case, it can explain why people tap around the 'spontaneous tempo' if they are asked to tap nor fast nor slow.

5. Conclusion

The present study dealt with common activities very close to our daily experiences. Walking on music turned out to be a rich and multidisciplinary research topic about which surprisingly little knowledge has been assembled yet. It combines relevant insights for music and rhythm perception research, music education, sports and handicapped training, and walking dynamics. We showed that people can synchronize their walking movements with music over a broad range of tempi, but that this synchronization is most optimal in a rather narrow range around 120 BPM. This finding can be connected with previous findings indicating that most music has a tempo in this range. It was shown that people walk faster on music than on simple metronome stimuli and further research will have to reveal what 'magical' power makes people walk faster. We started to shed some light on the question why people, although they differ so much in physical aspects, tend to converge in a narrow range in their long-term movement spectrum.

Appendix 1

Name	Meaning	Unit
Walking tempo	Walking steps per time unit	Steps/min ^a
Walking speed	Walking distance per time unit	km/h
Step size	Walking speed divided by walking tempo	m/step
Tapping tempo	Taps per time unit	Taps/min ^a
Nominal tempo	Tempo of the music as determined by the experts	Beats/min ^a

^a In the text BPM (Beats Per Minute) will be used, where beats stands for walking steps, finger taps or musical beats.

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