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Lost in the Rhythm: Effects of Rhythm on Subsequent Interpersonal Coordination

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Abstract

Music is a natural human expression present in all cultures, but the functions it serves are still debated. Previous research indicates that rhythm, an essential feature of music, can enhance coordination of movement and increase social bonding. However, the prolonged effects of rhythm have not yet been investigated. In this study, pairs of participants were exposed to one of three kinds of auditory stimuli (rhythmic, arrhythmic, or white-noise) and subsequently engaged in five trials of a joint-action task demanding interpersonal coordination. We show that when compared with the other two stimuli, exposure to the rhythmic beat reduced the practice effect in task performance. Analysis of the behavioral data suggests that this reduction results from more temporally coupled motor movements over successive trials and that shared exposure to rhythm facilitates interpersonal motor coupling, which in this context serves to impede the attainment of necessary dynamic coordination. We propose that rhythm has the potential to enhance interpersonal motor coupling, which might serve as a mechanism behind its facilitation of positive social attitudes.

Keywords: Rhythm; Interpersonal coordination; Motor coupling; Social bonding

1. Introduction

Music is omnipresent across all cultures and dates back to the evolutionary origins of *Homo sapiens* (Adler, 2009; Conard, Malina, & Münzel, 2009). Its ubiquity and

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conservation has led to various speculations about the societal functions music might serve (Dissanayake, 2006; Fitch, 2006; Huron, 2001). One key function appears to be the facilitation of cooperation and interpersonal coordination (Cross & Morley, 2008; Dunbar, Kaskatis, MacDonald, & Barra, 2012; Kirschner & Tomasello, 2010), yet the way in which music exerts this effect remains unknown. Brown (2000) proposes four possible routes through which music might function: group identity (e.g., anthems), group cognition (communication of ideas), group catharsis (synchronizing of emotions), and group coordination (synchronization and harmonization). While all four aspects are highly relevant, we were interested particularly in coordination; through shared sensory input, we believe that music facilitates the temporal organization of movements between individuals, and a number of studies have shown that such interpersonal coordination can subsequently increase social bonding (Hove & Risen, 2009; Reddish, Fischer, & Bulbulia, 2013; Shaw, Czekóová, Chromec, Mareček, & Brázdil, 2013; Wiltermuth & Heath, 2009).

The key element of music facilitating temporal coordination is rhythm—the metric organization of sounds. Rhythm enables groups of individuals to entrain to a common beat (Merker, Madison, & Eckerdal, 2009) and sustain stable motor patterns (McNeill, 1995). Interestingly, rhythmic entrainment appears to be an inborn human ability, observed even in infants (Phillips-Silver & Trainor, 2005; Winkler, Háden, Ladinig, Sziller, & Honing, 2009; Zentner & Eerola, 2010). Such audio-motor integration, or sensorimotor synchronization (SMS), has been investigated in numerous studies (for an extensive review see Repp & Su, 2013); these include tapping tasks (Chen, Zatorre, & Penhune, 2006; Dhamala et al., 2003; Konvalinka, Vuust, Roepstorff, & Frith, 2010), pendulum swinging (Schmidt, Richardson, Arsenault, & Galantucci, 2007; Varlet, Marin, Issartel, Schmidt, & Bardy, 2012), walking (Styns, van Noorden, Moelants, & Leman, 2007), rocking in chairs (Demos, Chaffin, Begosh, Daniels, & Marsh, 2012), and dancing (Miura, Kudo, Ohtsuki, & Kanehisa, 2011; Van Dyck et al., 2013). Together, these studies demonstrate the influence of rhythm on various aspects of motor coordination.

In all of the aforementioned studies, the effect of an auditory rhythmic stimulus was measured on an intrinsically rhythmic motor task (e.g., rhythmic tapping) performed synchronously to music. None of them assessed if the effects of rhythm on interpersonal coordination and social behavior can (a) extend beyond the period of listening and (b) manifest in tasks unrelated to an auditory stimulus. In other words, if rhythm remains an attractor of coordination, does this manifest even in tasks that pull participants away from rhythmic movement and create dissonance in motor structures?

The present study explored whether exposure to an auditory rhythm influences subsequent interpersonal coordination on a rhythmically unrelated task; specifically, a task that requires dynamic coordination rather than coupled motor performance. To isolate the effects of rhythm, we designed three conditions in which dyads listened passively to either a metrically structured beat (Rhythmic condition), a chaotic, unpredictable beat (Arrhythmic condition), or white-noise (Control condition). Following exposure to one of these stimuli, pairs of participants were tested on their ability to coordinate their movements on the labyrinth task employed by Valdesolo, Ouyang, and DeSteno (2010). These authors showed that joint synchronous action increased perceptual sensitivity to the movements of the other participant and subsequently enhanced coordination on this labyrinth task.

We selected this task specifically because it permits a dissociation between complementary motor coordination and motor coupling. While the former can consist of two different movements performed asynchronously but with the same underlying goal (tilting the labyrinth in opposite directions with varying angles to control the trajectory of the ball), the latter refers to movements performed with tight temporal and spatial synchrony. In terms of our research question, it allowed us to see if rhythm exerts a prolonged influence on participants' motor structures by pushing them towards motor coupling.

Since the labyrinth task requires dynamic, responsive, and fluid movements (thus high perceptual sensitivity to the other), we expected the rhythmic beat to attract dyads to more rhythmic, temporally coupled movements that are detrimental to performance in the labyrinth task. That is, we hypothesized that the rhythmic pattern will remain an attractor of coordination, thereby interfering with the responsiveness of participants' movements to one another. Furthermore, we predicted that motor coupling of participants in the Rhythmic condition would extend over multiple trials of the task, demonstrating the persistent influence of the rhythmic stimulus. We also assessed whether rhythm influences social attitudes toward interaction partners, predicting more positive attitudes among dyads in the Rhythmic condition.

2. Materials and methods

2.1. Participants

One hundred subjects (50 females; $M_{age} = 23.8$ years, range = 21–29 years) were recruited from the student population of Masaryk University, Brno, Czech Republic, and rewarded with course credits for participation. From this sample, 50 dyads comprised individuals of the same sex, same dominant hand, and similar height. Due to a malfunction of recording equipment, three dyads were omitted from the final analyses. The study protocol was approved by the ethical committee of Faculty of Arts, Masaryk University, and informed consent was obtained from all subjects.

2.2. Materials

In a double-blind design, dyads were divided randomly into three conditions defined by the type of auditory stimulus to which they were exposed before the labyrinth task—Rhythmic (15 dyads), Arrhythmic (16 dyads), and Control (16 dyads). The rhythmic and arrhythmic stimuli comprised the same number of kick and snare drum beats with strong bass line and tempo of 120 BPM. The only difference between these two stimuli was the metric pattern: Beats in the Rhythmic condition had a 4/4 metrical pattern with an inter-onset interval (IOI; or inter-beat interval) of 500 ms, and with a distinctive syncopation added to the "third" beat (the syncopation index described by Longuet-Higgins & Lee was 1; Fitch & Rosenfeld, 2007; Longuet-Higgins & Lee, 1984). Here, the kick drum arrives also on the pause between beat 3 and 4: "(1)kick$_{\text{-500 ms-}}$(2)snare$_{\text{-500 ms-}}$(3)kick$_{\text{-250 ms-}}$kick$_{\text{-250 ms-}}$(4)snare$_{\text{-500 ms}}$" (Butler, 2006). A syncopated rhythmic pattern was chosen over a simple metronome to simulate a more natural musical environment, which usually contains complex metric patterns (Large & Palmer, 2002; London, 1995). For the Arrhythmic condition, the beats comprising the rhythmic stimulus were distributed with random IOIs so as to eliminate any meter (IOIs ranged between 0 and 800 ms, with SD = 202.476 ms). The control stimulus was created by converting the rhythmic auditory stimulus to numbers via MATLAB; randomizing those numbers; and converting them back to auditory stimulus, producing a constant white-noise sound.

All stimuli were of identical durations (4 min). The rhythmic and arrhythmic stimuli were presented at 70 dB, while the control stimulus had, naturally, a lower volume of 43 dB. To ensure full and comparable attention was paid to the stimuli in all conditions, each stimulus was supplemented with 16 bell-ringing sounds that participants counted and reported in a subsequent questionnaire. Participants were told that the purpose of the study was to investigate the memory of sounds, and emphasis was placed on the bell-counting task.

2.3. Procedure

Dyads were seated back-to-back (0.7 m distance) and instructed not to move or talk during the auditory stimulus, thereby avoiding any social interaction. Subsequently, they stood facing each other at a distance of 0.5 m holding a wooden labyrinth (12 × 14 cm) with a steel ball (adopted from Valdesolo et al., 2010). Their task was to jointly navigate the steel ball through the labyrinth, and success was possible through one path only. Before the labyrinth task, participants were instructed to try to achieve the best possible time during five trials of the task.

To assess whether the rhythmic stimuli exerted a prolonged effect after exposure, completion times were recorded for each of the five trials. During the labyrinth task, hand-movement acceleration was recorded in three dimensions by ActiGraph Motion Sensors GT3X (John & Freedson, 2012) positioned on participants' wrists, operating at a sampling rate of 30 Hz.

At the end of the procedure, participants were separated into different rooms and asked to fill out a questionnaire. Items concerned the auditory stimuli (8 items), the labyrinth task (9 items), and the participants' partner (8 items), each scored by way of 140 mm visual analog scales (Bond & Lader, 1974) anchored by positive and negative extremes. Items about participants' partners were combined into four measures reflecting distinct attitudinal dimensions: closeness (the Inclusion of Other in the Self Scale; Aron, Aron, & Smollan, 1992), liking, dominance, and cooperation. Debriefing was performed at the end of data collection.

2.4. Data analysis

Raw hand-acceleration data were first preprocessed so as to allow the extraction of movements irrespective of directionality (see Appendix). Next, we investigated if the rhythmic beat to which participants in the Rhythmic condition were previously exposed remained an active attractor of coordination during the subsequent labyrinth task. Since successful performance on the labyrinth task demands movements of an aperiodic nature, it serves as a strong attractor that opposes simple phase-locking to the beat. As such, we considered a measure of relative phase to be inappropriate (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007). Instead, we estimated unintentional entrainment to the *frequency* of the rhythm, which would reduce the degrees of freedom necessary for coordination. In other words, rather than a simple one-to-one mapping of the beat and movement, we expected the movements of participants in the Rhythmic condition to be attracted by the most prominent frequency of the beat to which they were exposed previously. This situation is illustrated in Fig. 2A, where movements appear attracted to the frequency of the beat comprising the rhythmic stimulus, but performance on the labyrinth task serves to mask this entrainment.

To assess the strength of the beat as an attractor of coordination, a Fast Fourier Transform (FFT) was applied on the preprocessed hand-movement data. The frequency with maximal power was selected within a non-overlapping moving window of 7-s duration (as a compromise between temporal resolution and frequency resolution), and this was compared with the dominant frequency of the beat (Bruyn, Leman, Moelants, & Demey, 2009; Desmet, Leman, & Lesaffre, 2010). Since the beat had a dominant frequency of 2 Hz, synchronization within a window was detected when the movements of participants' hands had maximal power in this frequency, with a tolerance of $\pm$ 2 data points (1.76 and 2.31 Hz respectively). Importantly, participants with longer completion times experienced a greater interval after exposure to the auditory stimulus in their last trials compared to participants with shorter completion times. To control for this, we performed the FFT analysis on a time-window equal to the shortest hand-movement time-series (87.55 s = 12 windows). The ratio of synchronous to asynchronous windows was counted to obtain a percentage of time in which participants moved with a dominant movement frequency similar to the frequency of the rhythmic stimulus. Due to the length of the moving window, we were not able to analyze individual trials—there would be only approximately two windows per trial. Therefore, we report just the condition effects.

To quantify participants' interpersonal motor coupling, we employed cross-recurrence quantification analysis (CRQA) on the hand-movement data. CRQA is a phase-space based analysis that quantifies the coupling between two signals (Shockley, Butwill, Zbilut, & Webber, 2002), in our case the acceleration of participants' hands. When two signals follow the same trajectories in time, they run through the same phase-space neighborhood (defined by radius) and CRQA quantifies the extent to which two signals share that same neighborhood (Marwan, Romano, Thiel, & Kurths, 2007).

The time-series for each hand of participant A and B were paired on the basis of movements required for operating the labyrinth (i.e. dominant A–dominant B; and non-dominant A–non-dominant B; see Supplementary Materials, Fig. S1), and the measure of determinism (%DET) was computed using the MATLAB CRP Toolbox 5.17 (Marwan, Wessel, Meyerfeldt, Schirdewan, & Kurths, 2002). %DET is a percentage of recurrence points forming a diagonal line in a recurrence plot, thereby reflecting similar developments of trajectories and indicating predictability of the system (Marwan et al., 2007)—in our case, shared acceleration of hand movements (for details on CRQA analysis see Appendix, CRQA computation).

Due to the clustered nature of the hand-movement data, results from CRQA were analyzed with linear mixed-model regression (LMM) using SPSS (Version 21.0; IBM corp., Armonk, NY, USA). Using a step-down approach (West, Welch, & Galecki, 2007), all the logical fixed effects, interactions, repeated, and random effects were added initially to a base model and removed subsequently on the basis of improvement in the log-likelihood ratio ($p < .05$). This technique yielded the most parsimonious model, which still accounted for effects of clustering in the data (see Supplementary Material, *Equation 1*). In addition to CRQA measures, we were interested in the mean of movement acceleration and the total number of movements, as measured by the ActiGraphs (see Appendix, *Movement computation*). For the analysis of these data we created a second LMM (Supplementary Material, *Equation 2*). The Rhythmic condition was used as reference for both models, against which the Control and Arrhythmic conditions were compared.

3. Results

As a manipulation check, a one-way ANOVA was performed on ratings of perceived rhythmicity of the stimulus. This revealed a main effect of Condition ($F(2, 91) = 18.104$, $p < .001$), with post-hoc comparisons confirming that perceived rhythmicity was greater in the Rhythmic compared with the Arrhythmic and the Control condition (Gabriel correction; $ps < .001$).

3.1. Joint-action completion time

The time needed to complete the labyrinth task for each dyad and on each trial was analyzed with a two-way mixed-model ANOVA, in which Condition comprised the between-subject factor and Trial the repeated-measures factor. Contrary with our hypotheses, there was no main effect of Condition ($F(2, 44) = 1.258$, $p = .294$, $r = .06$). There was, however, a significant main effect of Trial ($F(4, 41) = 16.372$, $p < .001$),[1] revealing a linear decrease in completion time. We refer to this as the "practice" effect herein. Furthermore, there was a Condition × Trial interaction ($F(8, 84) = 2.427$, $p = .021$), revealing differences in the practice effect between conditions. Specifically, the differences in completion time across trials were significant for the Arrhythmic ($F(4, 41) = 14.397$,

$p < .001$) and Control conditions ($F(4, 41) = 6.143$, $p = .001$), but not for the Rhythmic condition ($F(4, 41) = 1.432$, $p = .241$).

Post-hoc pair-wise comparisons (Sidak corrections) revealed significant decreases in completion time between the first trial and all subsequent trials for the Arrhythmic condition ($ps < .001$). For the Control condition, significant decreases existed between the first trial and the third and fourth trials ($ps < .05$). There were no significant differences between trials in the Rhythmic condition. In other words, a greater practice effect was observed in the Control and Arrhythmic condition relative to the Rhythmic condition. This is presented in Fig. 1.

3.2. Movement kinematics

To achieve a more precise understanding of movement dynamics between individuals during the labyrinth task, we examined movement kinematics; specifically, we measured hand acceleration with ActiGraph Motion Sensors GT3X (ActiGraph; Pensacola, FL, USA). First, we tested if the dominant frequencies of the beat comprising the rhythmic stimulus manifests in the movements of individuals exposed to it previously; second, we assessed the number of movements and mean acceleration of movements for each individual; and third, we quantified interpersonal motor coupling in the labyrinth task.

The percentage of seconds that dyads moved at the same dominant frequency as the beat comprising the rhythmic stimulus was analyzed with a one-way ANOVA, where

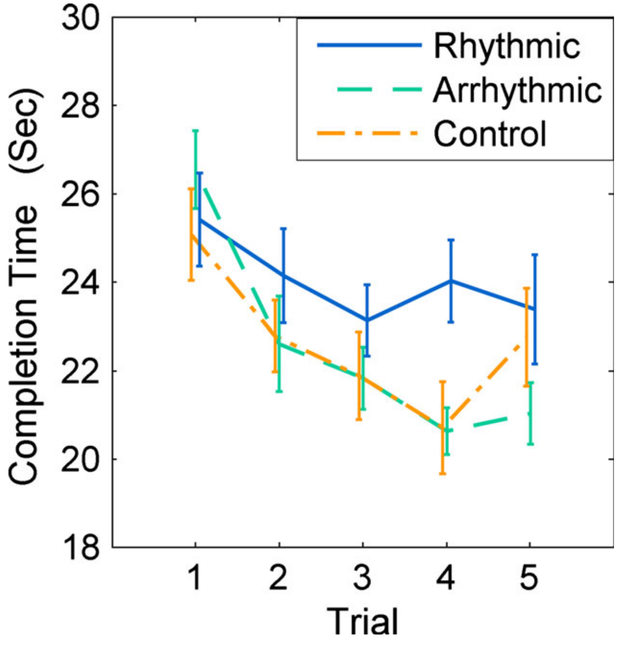

Fig. 1. Mean completion times of the labyrinth task for five trials with ±SEM, showing linear decrease in the Arrhythmic and Control conditions, but not in the Rhythmic condition.

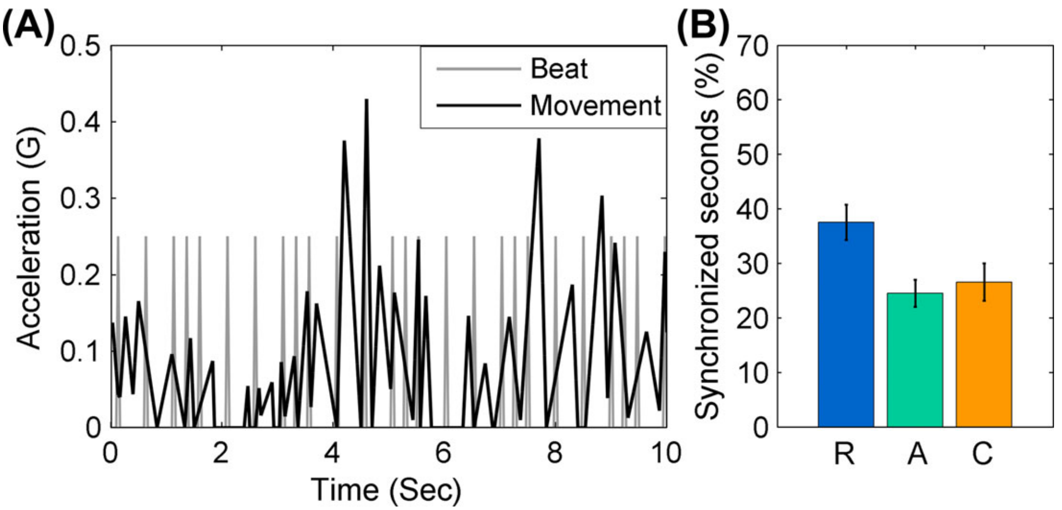

Fig. 2. (A) First 10 s of hand movements from a participant in the Rhythmic condition plotted against the occurrence of beats in a 10-s segment of the rhythmic stimulus. This illustrates the difference between timing of movements required by the labyrinth task and the structure of the rhythmic beat. (B) Results from a FFT analysis showing that participants in the Rhythmic condition exhibited movement frequencies similar to the beat for a higher percent of time. Error bars represent standard error. R = Rhythmic; A = Arrhythmic; C = Control.

Condition served as a between-subject factor. This demonstrated a significant effect of Condition ($F(2, 91) = 5.090$, $p = .008$), with post-hoc pair-wise comparisons (Gabriel correction) revealing a significantly higher percent of synchronized seconds in the Rhythmic compared to the Arrhythmic ($p = .011$) and Control conditions ($p = .041$). This effect is illustrated in Fig. 2.

The results of the linear mixed-model regressions (LMMs) applied to the number of movements, mean movement acceleration, and determinism (%DET) are summarized in Table 1, and fitted lines are plotted in Fig. 3. Converging with the completion time results, we did not observe any main effect of Condition (except for %DET), but we did observe differing patterns of movement parameters over trials across the three conditions. The importance of these variables for performance in the labyrinth task is supported by significant correlations of completion time with number of movements ($r = .442$, $p = .002$), mean acceleration ($r = -.577$, $p < .001$), and %DET ($r = .300$, $p = .041$).

While there was no difference between conditions in the number of movements executed on the first trial (no significant difference in intercepts), a significantly greater linear decrease in the number of movements was identified for the Arrhythmic and Control conditions compared to the Rhythmic condition. We also observed a significant difference in the trajectory of mean movement acceleration between the first and last trial in the Arrhythmic and Control conditions, but not in the Rhythmic condition (see Fig. 3A, B).

These findings are complemented further by the results from CRQA, which show a significantly lower decrease in %DET for the Rhythmic condition compared to the Control and Arrhythmic conditions (Fig. 3C). Although participants' movements in the Control

Table 1
Coefficients from mixed model regression on dependent variables from Actigraph data, measured over five trials

Variable	Intercept (Rhythmic)	Condition (Compared to Rhythmic)		Trial (Rhythmic)	Condition × Trial (Compared to Rhythmic)		Trial² (Rhythmic)	Condition × Trial² (Compared to Rhythmic)	
		Control	Arrhythmic		Control	Arrhythmic		Control	Arrhythmic
Number of movements	74.19 (3.69)**	3.77 (5.14)	5.20 (5.14)	−3.48 (1.78)	−5.39 (2.47)*	−6.27 (2.47)*	0.40 (0.27)	0.89 (0.37)*	0.83 (0.37)*
Mean acceleration	16.47 (1.69)**	−2.33 (2.35)	−3.25 (2.35)	−0.31 (0.63)	3.80 (0.88)**	2.35 (0.88)**	0.01 (0.08)	−0.42 (0.11)**	−0.26 (0.11)*
%DET	23.07 (3.09)**	8.04 (4.30)	10.06 (4.30)*	−1.09 (1.99)	−7.48 (2.77)**	−5.69 (2.77)*	0.17 (0.30)	1.14 (0.42)**	0.68 (0.42)

Notes. Trial expresses the linear effect, and Trial² expresses the quadratic effect. To avoid over-parametrization, the Rhythmic condition was set as a reference category. The variable Mean acceleration was multiplied by 100 for easier reading. *$p < 0.05$; **$p < 0.01$.

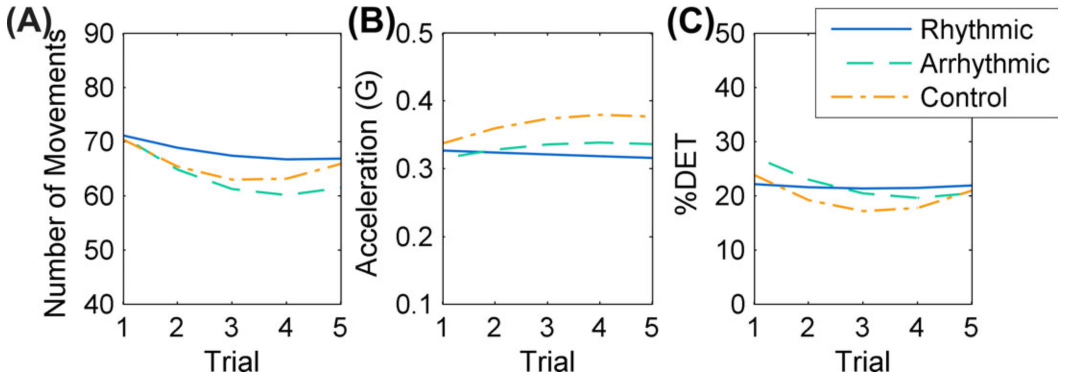

Fig. 3. Fit lines created on the basis of coefficients from the mixed-model regression applied to outcome variables from Actigraph data. Development of each trajectory is plotted against the five trials of the labyrinth task. Figures illustrate the difference between conditions in (A) the decrease in number of movements; (B) the increase of mean acceleration; and (C) the decrease in %DET.

and Arrhythmic conditions exhibited more coupling initially, they acquired more flexibility in a manner corresponding to the practice effect. No such effect was observed for the Rhythmic condition, however, where movements remained coupled across all five trials.

Together, these results demonstrate that the practice effect in the Rhythmic condition was significantly different compared to the Control and Arrhythmic conditions in measures of movement flexibility and responsiveness. In summary, the ActiGraphs uncover a logical, intuitive relationship between speed of task performance and movement kinematics.

3.3. *Questionnaire*

Of the four attitudinal measures (closeness, liking, cooperation, and dominance), only liking had a marginally significant difference between conditions ($F(2, 91) = 2.972$, $p = .056$), pointing to a higher liking in the Rhythmic condition compared to the Arrhythmic and Control conditions. However, post-hoc comparison revealed no significant differences between the Rhythmic and the other two conditions (Gabriel correction; Arrhythmic: $p = .074$, Control: $p = .158$). We also investigated correlations between liking and our measures of movement kinematics. This revealed a positive correlation between liking and %DET ($r = .283$; $p = .054$). In other words, greater motor coupling was related to greater interpersonal liking. Interestingly, our data also revealed a strong positive correlation between mean completion time of the labyrinth task and perceived liking ($r = .726$; $p = .002$) and closeness ($r = .727$; $p = .002$) in the Rhythmic condition only.

4. Discussion

In the present study, we investigated the influence of rhythm on subsequent interpersonal behavior. Specifically, we examined how pairs of individuals performed on a joint-action task after exposure to rhythmic, arrhythmic, or control auditory stimuli. This revealed three important findings: First, we observed that, having listened to a rhythmic beat, individuals' movements become more aligned to the frequency of that beat; second, we reveal that this apparent alignment to the rhythm manifests even in the face of task demands, interfering with dynamic interpersonal coordination; and third, we show that when alignment to the rhythmic stimulus occurs in two interacting individuals, manifesting as increased motor coupling, their interpersonal attitudes toward one another become more positive.

To assess the effects of rhythm on interpersonal motor behavior, we employed a specific joint-action task—the labyrinth game. Successful completion of this structured and complex task demands flexible and complementary timing of movements between two individuals; they are required to respond dynamically to each other's movements, acting as an interactive pair rather than a synchronized unit. The strong practice (i.e., Trial) effect reveals that participants learned to coordinate their movements over repeated trials. Importantly, however, the Trial × Condition interaction shows that this improvement in completion time occurred only for pairs exposed to the arrhythmic and control stimuli. We propose that, over the course of five trials, participants' movements in the Rhythmic condition were attracted to the frequency of the rhythmic stimuli, which served to inhibit the responsive, reactive, and complementary movements achieved with practice in the other conditions.

In support of this claim, we showed that the frequencies of hand movements performed by participants in the Rhythmic condition were more synchronized to the dominant frequencies of the rhythmic beat than those of participants in the other conditions.

Next, we observed a decrease in the number of movements over successive trials in the Control and Arrhythmic conditions, but not in the Rhythmic condition. Successful performance on the labyrinth game requires complementary and responsive movements between individuals to navigate the ball through the narrow corridors and turns comprising the maze. Simultaneous movements led to overshooting, which then require additional corrective adjustments. Furthermore, differences between the conditions vis-à-vis the practice effect in hand-movement acceleration indicate a lower reduction in movement variability across trials in the Rhythmic condition relative to the Arrhythmic and Control conditions. These results show that hand movements in the Rhythmic condition expressed low acceleration and lack of spatial movement freedom across successive trials. Finally, our CRQA supplemented these other measures by demonstrating similar movement patterns between the hands of individuals exposed to the rhythmic auditory stimulus. An absence of decrease in %DET for the Rhythmic condition corresponds to the decreased variability of movements at the level of dyads. Since %DET is a measure of periodicity and predictability of a signal, this finding is indicative of repetitive and predictable movement acceleration.

In this light, the absence of a Condition effect on completion time and movement kinematics might at first glance contradict this interpretation, since it may be predicted that rhythm would produce the strongest negative effect directly after it was perceived, and attenuate with time. However, we suggest that this finding reflects the very nature of human task-sharing and joint-action co-representation; while task-sharing concerns overall goals and intentions, action co-representation reflects the mechanics of labor division, including anticipation of our interaction partners' movements and adapting our own movements accordingly (De Bruijn, Miedl, & Bekkering, 2011; Holländer, Jung, & Prinz, 2011; Pezzulo & Dindo, 2011; Sebanz, Bekkering, & Knoblich, 2006; Sebanz, Knoblich, & Prinz, 2005; Wenke et al., 2011). Since our participants did not interact with each other prior to the labyrinth game, they shared a task goal, but lacked co-representation of the other's actions. Such lack of experience presumably prevented successful anticipation of the other's movements in the first trial and initially inhibited necessary responsiveness, resulting in coupled rather than complementary movements in all conditions (reflected in our measure of %DET). In contrast, the improved performance over increasing trials in those participants in the Arrhythmic and Control conditions suggests their ability to achieve better coordination with one another. It is thus likely that better alignment between partners' co-representations of their actions (see Pezzulo & Dindo, 2011) allowed them to adapt their actions accordingly. The significant trial effect in %DET might reflect this (for similar results, see Knoblich & Jordan, 2003; Newman-Norlund, Bosga, Meulenbroek, & Bekkering, 2008; Van der Wel, Knoblich, & Sebanz, 2011). Such alignment was not observed in the Rhythmic condition, and we speculate that during the five trials rhythm masked sensitivity to one-another's movements by attracting them to a set frequency.

Our interpretation of the findings is in line with previous research in dynamic attention theory (DAT; Escoffier, Sheng, & Schirmer, 2010; Large & Jones, 1999), which showed that rhythm is a strong attractor of attention, even if it impairs performance (Brochard, Tassin, & Zagar, 2013). Moreover, auditory stimuli have been shown to be more powerful than visual in driving movements (Chen, Repp, & Patel, 2002; Repp & Penel, 2002, 2004; Varlet et al., 2012), which supports the interpretation that the auditory rhythm resonating in participants' motor structures (Nozaradan, Peretz, Missal, & Mouraux, 2011) might in some instances decrease perceptual sensitivity to one another (Demos et al., 2012). In other words, perceptuo-motor processes might be influenced by a rhythmic beat in a way that interferes with the complementary temporal behavior required for the labyrinth task.

We further speculate that shared listening to rhythm serves to entrain a common timing behind interpersonal motor coding. Although our measurements provide no direct evidence for such an effect, several neuroscientific findings lend support to this interpretation. For example, the interplay between motor and auditory systems has been demonstrated by several studies that identify specific brain structures (premotor cortex, supplementary motor area, and cerebellum) engaged during passive listening to rhythmic music (Baumann et al., 2007; Chen, Penhune, & Zatorre, 2009; Grahn & Brett, 2007; Lahav, Saltzman, & Schlaug, 2007; Schubotz, Friederici, & von Cramon, 2000). These neural systems are necessary for preparing, timing, sequencing, and coordinating movement, as well as for the production of rhythm (Dhamala et al., 2003). From this evidence we might conjecture that rhythm activates the neural motor circuits of two participants in a similar manner corresponding to the structure of the beat.

Interestingly, our data lends further empirical support to the hypothesis that motor coupling can increase positive affect toward other individuals (Miles, Nind, & Macrae, 2009;

Reddish, Bulbulia, & Fischer, 2013; Valdesolo & Desteno, 2011; Wiltermuth & Heath, 2009). In contrast with the previous studies, however, our finding is based on spontaneous motor coupling induced by rhythm rather than on predefined synchronous movement patterns. While more evidence is needed before any firm interpretation is justified, our findings may go some way toward an explanation for the natural connection between music, movement, and social bonding. Such an interpretation would be supported by the positive correlation between the measure of motor coupling (%DET) and liking. Moreover, liking and closeness in the Rhythmic condition correlated positively with completion time, suggesting that increased motor coupling was associated with impaired task performance on one hand, but enhanced positive attitudes on the other (Demos et al., 2012).

It is important to acknowledge potential limitations with the present study, which may be addressed by future investigations. First, the metric structure that we used was familiar among participants due to its frequent use in popular songs in the cultural milieu of the Czech Republic, and it remains to be seen whether this meter would also work in other cultures with different musical traditions. It is necessary, therefore, to investigate metric structures cross-culturally and to assess whether alternative structures yield different results (Chen et al., 2006). For example, it might be fruitful to compare the effects of various meters and tempos on motor co-ordination; to design a rhythmically related task to observe how an extension of the beat influences interpersonal motor coordination (e.g., rowing, where precise movement timing and power are required to keep a boat on a straight trajectory); to expose each participant to a stimulus with different rhythmic pattern; or to measure the temporal extent of motor coupling between individuals (e.g., using the automatic imitation paradigm; see Shaw et al., 2013). Alternatively, neuroimaging techniques might be utilized to assess the degree to which rhythmic beats are capable of tuning two individuals' neural motor circuits.

In summary, our study sheds new light on the potential mechanisms underlying the effects of music on social behavior. We have proposed that our findings indicate that collective listening to music impacts on subsequent interpersonal behavior through its enhancement of motor coupling between individuals. However, given that we did not observe any main effects in our measurements, more empirical data are needed to test this claim. Furthermore, our findings also suggest that listening to rhythm does not uniformly aid interpersonal interaction; such motor coupling may be detrimental to interactions that require dynamic, coordinated motor responses. Our study therefore provides preliminary empirical evidence for a more nuanced interpretation for the impact of rhythm on interpersonal behavior and its potential functions in human ceremonies, rituals, and social gatherings.

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Note

1. We are reporting multivariate tests because Muachley's test indicated that the assumption of sphericity had been violated ($\chi^2(9) = 17.489$, $p = .042$),

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Illustration of the labyrinth task and different types of hand interactions. Green = dominant hands interaction; Yellow = non-dominant hands interaction. The close caption illustrates how interactions between these hand types capture most effectively the degree of interpersonal co-ordination: by steering the ball in a diagonal direction, it traveled faster than by using horizontal and vertical directions that would correspond to non-dominant – dominant hands interactions.

Appendix:

CRQA computation

Before submitting the ActiGraph data to CRQA, preprocessing was performed in MATLAB (2013; MathWorks Inc., Natick, MA, USA). In an initial step, a single acceleration vector was calculated for each hand by collapsing across the three spatial dimensions, and then zero-centering and rectifying the collapsed time-series. In a second step, each acceleration vector was *z*-scored. This ensured that the CRQA results were based truly on the sequence of accelerations in time, and did not result simply from greater differences or commonalities between participants' hand movement acceleration amplitudes (Shockley et al., 2002).

To conduct CRQA, the first step is to reconstruct the phase space by selecting an appropriate embedding dimension and a time-delay based on Taken's theorem (Takens, 1981; Zbilut, Zaldivar-Comenges, & Strozzi, 2002). We applied the function of average mutual information to select a suitable time-delay which yielded delays from 2 to 10. A delay of five sampling points was chosen because it corresponded to a minimal time difference between movements (i.e. 6 Hz, see *Movement computation*). Next, we applied the function of false nearest neighbors (Kennel, Brown, & Abarbanel, 1992) and estimated embedding dimensions that ranged from 3 to 8. As over-embedding yields more reliable CRQA results than under-embedding (Marwan et al., 2002; Webber & Zbilut, 2005), we chose an embedding dimension of 6 as a compromise between the average and upper estimates of the dataset. A radius was set so as to have an average recurrence rate (%RR —ratio of points in the phase space counted as recurrent) around 3% to ensure that all subjects have non-zero %RR (Shockley, 2005).

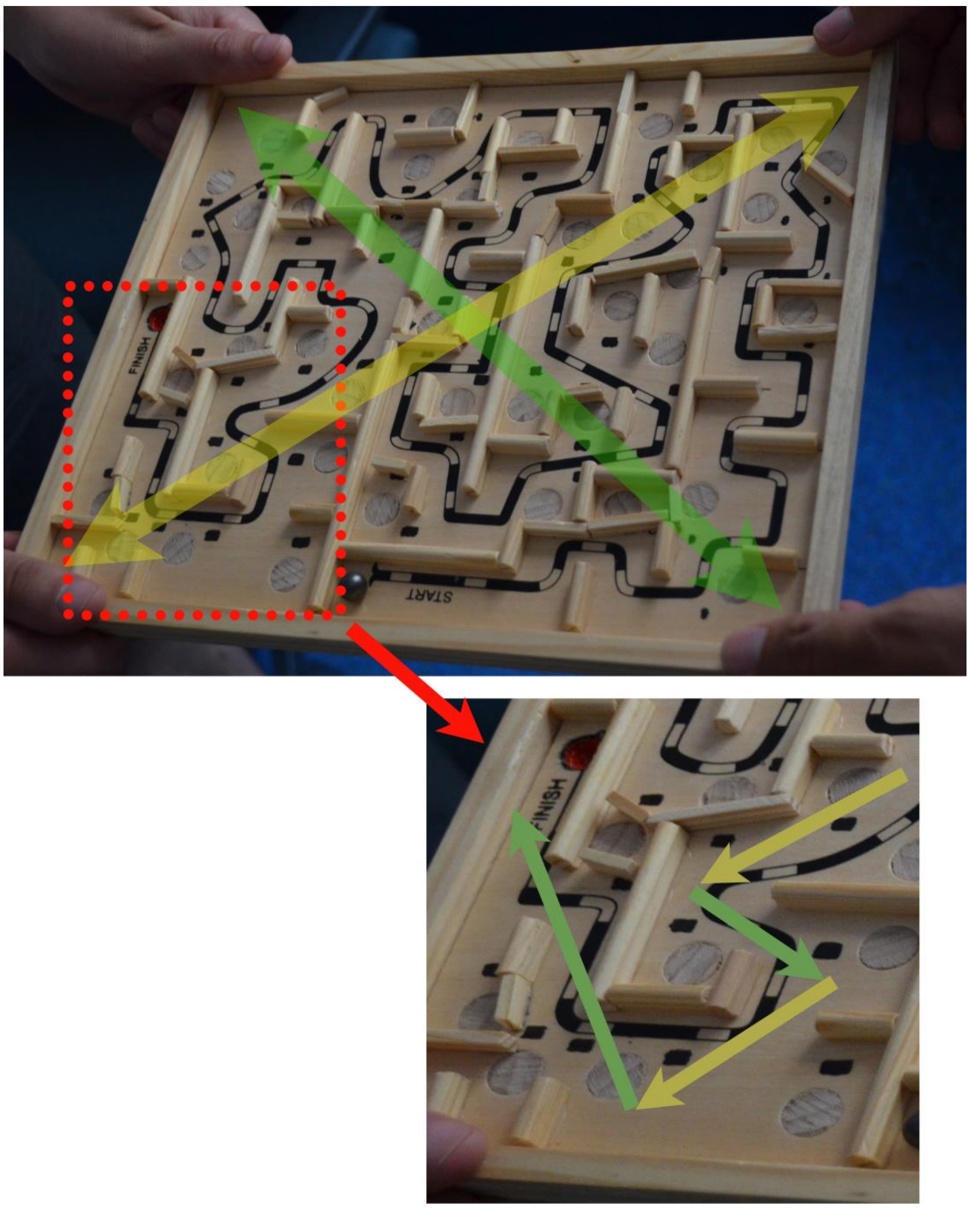
Movement computation

To extract hand movements from the raw ActiGraph signal, we first recorded the smallest and fastest movements which served as a definition of minimal movement. This yielded minimal movement acceleration of 0.05 G and minimal distance between movements of 166 ms (movement frequency of 6 Hz). Next, we used the collapsed and rectified time-series and excluded all movements smaller than 0.05 G and closer than 166 ms (for an example see Fig. 2a). Such defined time-series were used to compute mean number of movements and mean acceleration.

Supplementary Material

Illustration 1.

Illustration of the labyrinth task and main hand interactions. Green = dominant hands interaction; Yellow = non-dominant hands interaction. The close caption illustrates how interactions between these hand types capture most effectively the degree of interpersonal co-ordination.



Equation 1.

$\text{Variable}_{t|i|j} = \beta_0 + \beta_1 \text{ (Trial)} + \beta_2 \text{ (Trial}^2) + \beta_3 \text{ (Condition = [Rhythmic vs. Control])} + \beta_4 \text{ (Condition = [Rhythmic vs. Arrhythmic])} + \beta_5 \text{ (Condition-by-Trial = [Rhythmic vs. Control])} + \beta_6 \text{ (Condition-by-Trial = [Rhythmic vs. Arrhythmic])} + \beta_7 \text{ (Condition-by-Trial}^2 \text{ = [Rhythmic vs. Control])} + \beta_8 \text{ (Condition-by-Trial}^2 \text{ = [Rhythmic vs. Arrhythmic])} + u_{0j} + u_{1j} \text{ (Trial)} + \varepsilon_{t|i|j}$

In the specification above, *Variable* represents the value of %DET for trial *t* and interaction of two hands (as mentioned above) *i* nested within dyad *j*. *Trial* represents the linear effect of learning and $Trial^2$ the quadratic effect. To examine differences in movement kinematics between conditions, the Rhythmic condition was set as a reference category against which all other conditions were compared (β_3-β_8). u_{oj} represents a random intercept and u_{1j} a random slope for a dyad *j*; $\varepsilon_{t|i|j}$ represents the unstructured variance of residuals across repeated trials.

Equation 2.

$\text{Variable}_{t|i|j|k} = \beta_0 + \beta_1 \text{(Trial)} + \beta_2 (\text{Trial}^2) + \beta_3 \text{(Condition = [Rhythmic vs. Control])} + \beta_4 \text{(Condition = [Rhythmic vs. Arrhythmic])} + \beta_5 \text{(Condition-by-Trial = [Rhythmic vs. Control])} + \beta_6 \text{(Condition-by-Trial = [Rhythmic vs. Arrhythmic])} + \beta_7 (\text{Condition-by-Trial}^2 = \text{[Rhythmic vs. Control])} + \beta_8 (\text{Condition-by-Trial}^2 = \text{[Rhythmic vs. Arrhythmic])} + u_{0j} + u_{0k} + u_{1k} \text{(Trial)} + \varepsilon_{t|i|j|k}$

In the model above, *Variable* represents the value of the dependent variable for trial *t* and hand *i* in person *j*, nested within dyad *k*. β_0 is intercept (i.e. the Rhythmic condition), Trial represents the linear practice effect, and *Trial*^{2} the quadratic effect. β_3-β_8 are comparisons between conditions and condition-by-trial interactions. u_{0j} represents a random intercept for a person, u_{0k} represents a random intercept for a dyad *k*, and u_{1k} is a random linear slope. Again, $\varepsilon_{t|i|j|k}$ represents the unstructured variance of residuals across repeated trials.