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# Embodied Metre in Spontaneous Movement to Music

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## ABSTRACT

Listening to music is often associated with spontaneous body movements, frequently synchronized with its periodic structure. The notion of embodied cognition assumes that intelligent behavior does not emerge from mere passive perception, but requires goal-directed interactions between the organism and its environment. According to this view, one could postulate that we use our bodily movements to help parse the metric structure of music. The aim of the study was to investigate how pulsations on different metrical levels are manifested in spontaneous movement to music. Participants were presented with a piece of instrumental music in 4/4 time, played in five different tempi ranging from 92 BPM to 138 BPM. They were instructed to move to the music, and their movements were recorded with an optical motion capture system. Subsequently, methods of signal processing and Principal components analysis were applied in order to extract eigenmovements synchronized with different metrical levels. We found differences between metric levels in terms of the prevalence of synchronized eigenmovements. For instance, mediolateral movements of arms were found to be frequently synchronized to the tactus level pulse, while rotation and lateral flexion of the upper torso were commonly found to exhibit periods of two and four beats, respectively. The results imply that periodicities on several metric levels are simultaneously present in spontaneous movement to music. This could suggest that the metric structure of music is encoded in such spontaneous movements.

## I. INTRODUCTION

Music and bodily movement are closely linked, and in most cultures music and dance are inseparable (Arom, 1991; Cross, 2003). According to a questionnaire study (Lesaffre 2005), 95% of people report that they move with music. Music has been found to affect the way people walk (Styns, van Noorden, Moelants, & Leman, 2007), with people tending to walk faster with music than with metronome stimuli. Moreover, Repp and Penel (2004) have found that auditory rhythms can evoke rhythmic bodily movement more efficiently than visual rhythms.

Often, the movements associated with music are synchronized with the beat, or tactus, of the music. The latter refers to the subjective sense of periodicity in music evoked by temporal regularities in the acoustical signal. Listeners' ability to synchronize with the beat of the music has to date been mostly investigated with tapping studies. According to these studies, synchronization ability is spontaneous and accurate (Drake, Penel, & Bigand, 2000; Snyder & Krumhansl, 2001; Toiviainen & Snyder, 2003) and is associated with a preferred pulse period near 500 ms (Fraisse, 1982; Parncutt, 1994; van Noorden & Moelants, 1999).

In addition to the tactus, we perceive other pulses with different periods. These are often hierarchically organized, with their periods being integral multiples of the basic pulse period (Palmer & Krumhansl, 1990). The interaction between these different pulse sensations results in a percept of periodically alternating between strong and weak beats, corresponding to the generally accepted definition of meter (Lerdahl & Jackendoff, 1983).

While music undoubtedly induces movement, there is also some evidence to suggest that movement affects beat perception. Todd, Cousins and Lee (2007) found that 16 per cent of variation in preferred beat rate can be predicted from anthropometric factors, such as weight as well as length and width of certain body segments. Phillips-Silver and Trainor (2007) found that infants' perception of meter can be affected by the way they are swayed while listening to rhythmic sequences. In fact, Todd, O'Boyle, and Lee (1999) propose that pulse is an inherently sensorimotor phenomenon in the sense that pulse perception necessarily involves motor system activity.

While there exists a substantial body of work on synchronization with a musical beat (e.g., Repp, 2005a, 2005b; Snyder & Krumhansl, 2001; Toiviainen & Snyder, 2003), the kinematic aspects of this activity have been investigated to a lesser extent. However, Eerola, Luck and Toiviainen (2006) investigated toddlers' corporeal synchronization with music using a high-definition motion-capture system. They found that 2-4 year old children exhibited periodic movement, and that this movement was at times synchronized with music. Luck and Toiviainen (2006), in a study on ensemble musicians' synchronization with conductors' gestures, found that the ensemble's performance was most highly synchronized with periods of maximal negative acceleration along the trajectory. Using point-light representations of conducting gestures in a synchronization task, Luck and Sloboda (2008) investigated how perceived visual pulse depends on the kinematic properties of these gestures. They found that acceleration along the trajectory was the best predictor of perceived beat, followed by high instantaneous speed.

The present work investigates the nature of spontaneous movements to music, focusing on how pulsations on different metrical levels are manifested in spontaneous movement to music. To this end, we apply kinetic analysis, body modelling, dimensionality reduction and signal processing to data acquired using a high-resolution motion capture system to identify the most typical movement patterns synchronized with different metrical levels.

## II. METHOD

### A. Participants

A total of 32 participants took part in the study. Following the data collecting process, eight participants were excluded from further analysis due to either technical problems or because markers had been placed inappropriately for the requirements of the present study. This left a total of 24 participants (16 females, 8 males, mean age = 24.2, std of age = 3.9) for subsequent analysis. These participants were predominantly Finnish university students (75%) with the remainder comprised of international exchange students of various nationalities. The average number of years of formal musical training was 8.0 (std = 6.7); 87.5 % of those with musical training had trained for 10 years or more. Most participants stated that they enjoyed dancing at home or in a nightclub (58.3%), with an average time spent dancing of 2 hours per week (std = 2.6 hours), while a minority (25%) of the participants had had formal dance or aerobics training. Additionally, participants were asked how many hours per week they spent doing physical activities or sports, of which the average was 5.1 hours (std = 4.1 hours). Participants received an honorarium in the form of a movie ticket for their participation in the study.

### B. Apparatus

Participants' movements were recorded using a high-quality eight-camera optical motion capture system (Qualisys ProReflex). The system tracked the movement of reflective markers placed on each participant at a frame rate of 60 Hz. The trajectories were interpolated together to create a three dimensional point-light display of each participant. The motion capture data was synchronized with the musical stimulus using the TTL pulses transmitted by the Qualisys cameras. The musical stimulus was played back from a Pure Data (Pd) patch running on an Apple computer. Both the audio and the TTL pulses were routed to the inputs of a Digidesign Mbox and recorded using ProTools software. For reference purposes, the sessions were additionally videotaped using a Panasonic Mini DV camcorder.

### C. Procedure

Participants were recorded individually, and prior to each motion-capture session, a total of 28 reflective markers were attached to the participant's body. The locations of the markers were as follows (L = left, R = right, F = front, B = back): 1: LF head (L frontal eminence); 2: RF head (R frontal eminence); 3: LB head (L dorsal parietal bone); 4: RB head (R dorsal parietal bone); 5: L shoulder (L scapular acromion); 6: R shoulder (R scapular acromion); 7: spine (midpoint between the superior angles of the scapulae); 8: breastbone (sternum); 9: LF hip (L anterior superior iliac spine); 10: RF hip (R anterior superior iliac spine); 11: LB hip (L posterior superior iliac spine); 12: RB hip (R posterior superior iliac spine); 13: L elbow (L olecranon); 14: R elbow (R olecranon); 15: L inner wrist(L distal radius); 16: L outer wrist (L distal ulna); 17: R inner wrist (R distal radius); 18: R outer wrist (R distal ulna); 19: L middle finger (metacarpophalangeal joint of L digitus medius); 20: R middle finger (metacarpophalangeal joint of R digitus medius); 21: L knee (L lateral distal femur); 22: R knee (R lateral distal femur); 23: L ankle (L lateral malleolus); 24: R ankle (R lateral malleolus); 25: L little toe (L 5th proximal phalanx); 26: L big toe (distal interphalangeal joint of L hallux); 27: R little toe (R 5th proximal phalanx); 28: R big toe (distal interphalangeal joint of R hallux). The locations of the markers are depicted in Figure 1.a.

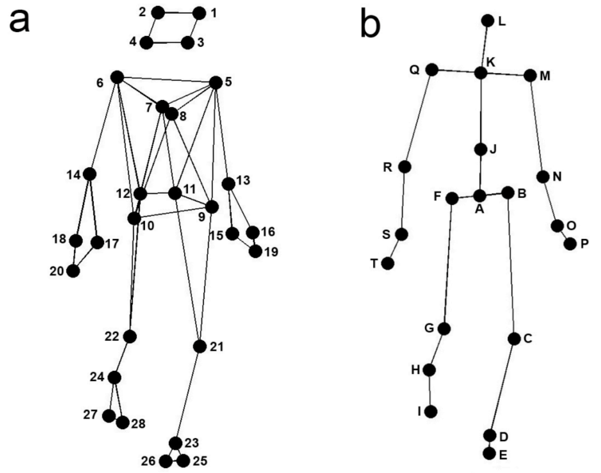

**Figure 1. a) Anterior view of the location of markers attached to the participants' bodies. b) Anterior view of the locations of the secondary markers used in the analysis (see text below). Neighboring joints in kinematic chains are connected with lines.**

Once the markers were attached and well placed, we ensured that they were non-intrusive to the participant's mobility, and that the participant was comfortable with the apparatus and the setting. The participant stood in the centre of the capture area and was instructed to 'move freely' to the music.

### D. Stimulus

Participants were presented with an instrumental 12-bar blues progression performed in a minor key and 4/4 meter. During the piece, the progression was repeated five times at five different tempi ranging from 92 to 138 beats per minute (BPM) and presented in random order.

## III. RESULTS

To start the computational analysis, a set of secondary markers, subsequently referred to as the joints, was derived from the marker locations. This was done in order to make the movement data compatible with the body-segment model used in subsequent analyses. The new set of twenty joints is depicted in Fig.1.b. The locations of joints C, D, G, H, M, N, P, Q, R, S, and T are identical to the locations of one of the markers, while the locations of the other joints were obtained by averaging the locations of two or more markers. In addition to the joints obtained by the calculation described above, Figure 1.b displays as lines the body segments that connect the joints.

The body segments considered in this study comprise five kinematic chains, that is, chains of body segments connected by joints. These are (see Fig. 1.b): ABCDE (left hip; left thigh; left leg; left foot), AFGHI (right hip; right thigh; right leg; right foot), AJKL (abdomen; thorax; head and neck), AJKMNOP (abdomen; thorax; left shoulder; left upper arm; left forearm; left hand), and AJKQRST (abdomen; thorax; right shoulder; right upper arm; right forearm; right hand).

The instantaneous velocity and acceleration of joint locations as well as angular velocity and acceleration of segment direction vectors were estimated by numerical differentiation. To this end, we used the Savitzky-Golay smoothing FIR filter (Braci & Diop, 2003) with a window length of seven samples and a polynomial order of two. These values were found to provide an optimal combination of precision and smoothness in the time derivatives.

### E. Mechanical energy

For the estimation of kinetic variables, we used the body segment model proposed by Dempster (Robertson, Caldwell, Hamill, Kamen, & Whittlesley, 2004). The model specifies a number of parameters for each of the body segments. These are the mass of the segment in relation to the total body mass, the distance of the center of mass from the proximal joint in relation to the segment length, and the radius of gyration in relation to segment length with respect to the center of mass, the proximal joint, and the distal joint.

As a first step in the kinetic analysis, we estimated the total instantaneous potential and kinetic energy of the body, averaged across participants and across 4-beat segments in the stimuli. The average energies are shown in Fig. 2. As can be seen, the average potential energy displays a clear periodicity at the one-beat level, the beat location closely matching with the point of maximal decrease in potential energy and thus maximal downward velocity of the body. Average kinetic energy, on the other hand, displays a clear superposition of half-beat and two-beat periods.

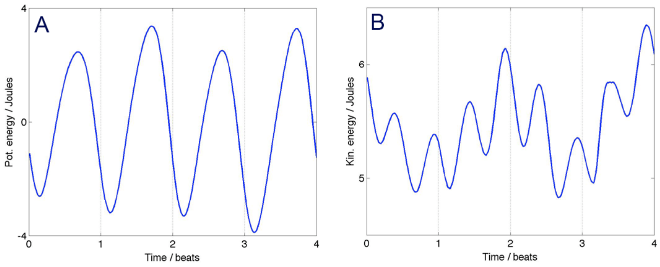

**Fig. 2. Total potential (A) and kinetic (B) energy of the body, averaged across participants and 4-beat segments.**

Subsequently, we performed a more detailed periodicity analysis of the components of mechanical energy. To this end, we estimated the period of potential and kinetic energy in each 4-beat segment of the data using autocorrelation, and estimated the period distribution using kernel density estimation. Fig. 3 displays the distribution of periods for potential energy. As can be seen, the most common periodicity for most tempi corresponds to the length of one beat, with a two-beat period being the second most prominent. An exception is the tempo 92 BPM, for which the two-beat period is the most prominent.

Fig. 4 shows the distribution of estimated period for kinetic energy. In this case, the most common periodicity for each tempo corresponds to the length of two beats, while four-beat periods are also relatively common.

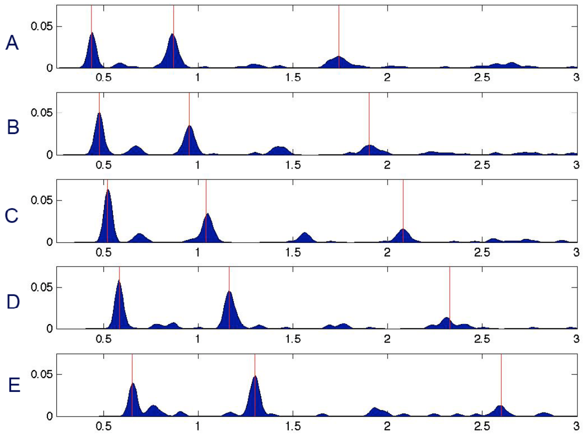

**Fig. 3. Distribution of periodicities for potential energy for each of the five tempi. A. 138 BPM; B. 126 BPM; C. 115 BPM; D. 103 BPM; E. 92 BPM. In each subplot, the vertical lines display the length of one, two, and four beats in the stimulus.**

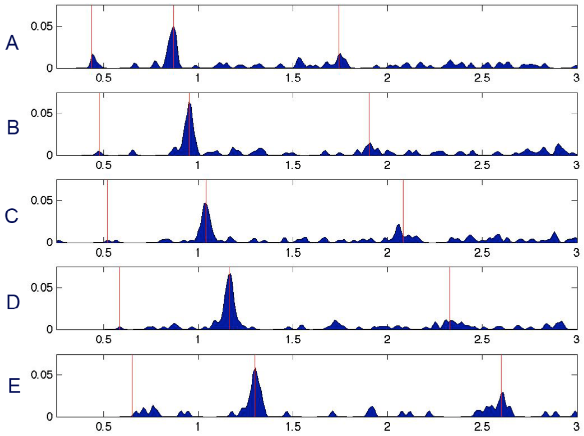

**Fig. 4. Distribution of periodicities for kinetic energy for each of the five tempi. A. 138 BPM; B. 126 BPM; C. 115 BPM; D. 103 BPM; E. 92 BPM. In each subplot, the vertical lines display the length of one, two, and four beats in the stimulus.**

### F. Eigenmovements

Next, we extracted typical movement patterns from the data and investigated their periodicities. To this end, the data was decomposed into 8-beat sections with 50% overlap between neighbouring sections. This decomposition was carried out because many of the participants changed their movement patterns during presentation of the stimuli. The decomposition resulted in 55 sections for each participant (11 sections for each tempo). Subsequently, a Principal Components Analysis (PCA) was carried out separately for each participant and each section.

The first three Principal Component projections from each PCA were subjected to a periodicity analysis using autocorrelation. Using a tolerance of 10%, we found that that 4% of the Principal Components were synchronized with the one-beat level, while 16% and 20% were synchronized with the two-beat and four-beat levels, respectively. The rest of the

Principal Component projections either had another period or were aperiodic.

To investigate the prevalence of different movement patterns on various metrical levels, a second (between-subjects) PCA was carried out on the eigenmovements (i.e., Principal Components obtained from the first PCA) that were synchronized with one of the three metrical levels (one, two, or four beats).

As a general remark, we observed differences between the three metrical levels in terms of the distribution of the secondary PC projections. In a more detailed analysis, we detected the most typical movements for each of the three metrical levels by identifying the synchronized eigenmovements whose PC projections displayed the highest variance. This analysis suggested the following most typical eigenmovements for each of the metrical levels.

- One-beat level: (1) mediolateral arm movements; (2) vertical hand and torso movements;
- Two-beat level: (1) mediolateral arm movements; (2) rotation of the upper torso;
- Four-beat level: (1) lateral flexion of the body; (2) rotation of the upper torso.

Fig. 5 displays these eigenmovements schematically[1].

## IV. DISCUSSION

We investigated spontaneous movement to music, with a special emphasis on the relationship between movement patterns and metrical levels of music. A kinetic analysis of the movement data revealed that the average potential energy displayed a period of one beat, with the location of the beat closely corresponding to the point of maximal instantaneous decrease of potential energy and thus maximal overall downward velocity of the body. The kinetic energy, on the other hand, displayed a superposition of periods of half a beat and two beats. A more detailed analysis of periodicities in the different forms of mechanical energy of the body showed that the most common periods for potential energy were one and two musical beats, while those for kinetic energy were two and four beats. These observations suggest that the various metrical levels of the musical stimulus were embodied as different forms of mechanical energy.

Subsequently, we performed a two-stage Principal Components Analysis and periodicity analysis on the movement data in order to find typical movement patterns that were synchronized with each of the three main metrical levels of the musical stimulus. The results of this analysis revealed differences in terms of the prevalence of eigenmovements between the different metrical levels. In particular, the tactus level was associated with mediolateral arm movements as well as vertical hand and torso movements, the two-beat level with mediolateral arm movements and rotation of the upper torso, and the four-beat level with lateral flexion of the torso and rotation of the upper torso.

The results imply that periodicities on several metric levels are simultaneously present in spontaneous movement to music. This could suggest that the metric structure of music is encoded in such spontaneous movements.

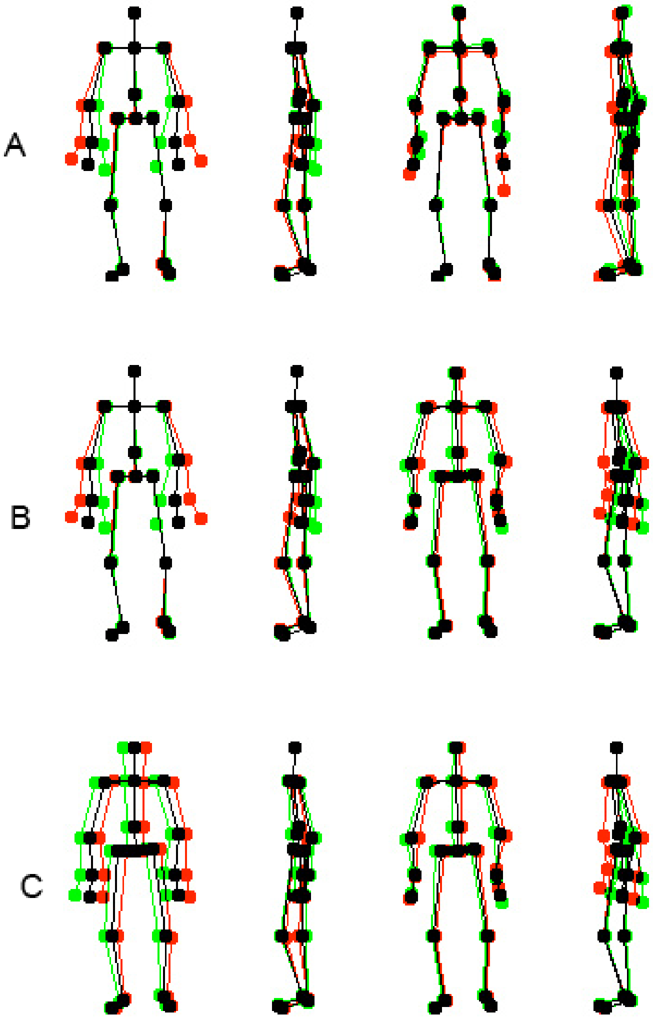

**Fig. 5. Typical eigenmovements for periods of (A) one beat; (B) two beats; (C) four beats. Each eigenmovement is displayed with both a frontal and a lateral view. The mean posture of the eigenmovement is displayed in black, while the points with maximal deviation from the mean posture are displayed in red and green.**

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[1] An animation of the eigenmovements is available on the internet at http://dl.getdropbox.com/u/567596/eigenmovements.mov

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