

Moving to the Beat:

Studying Entrainment to Micro-Rhythmic Changes in Pulse by Motion Capture

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Abstract

Pulse is a fundamental reference for the production and perception of rhythm. In this paper, we study entrainment to changes in the micro-rhythmic design of the basic pulse of the groove in ‘Left&Right’ by D’Angelo. In part 1 of the groove the beats have one specific position; in part 2, on the other hand, the different rhythmic layers specify two simultaneous but alternative beat positions that are approximately fifty to eighty milliseconds apart. We first anticipate listeners’ perceptual response using the theories of entrainment and dynamic attending as points of departure. We then report on a motion capture experiment aimed at engaging listeners' motion patterns in response to the two parts of the tune. The results show that when multiple onsets are introduced in part 2, the half note becomes a significant additional level of entrainment and the temporal locations of the perceived beats are drawn towards the added onsets.

Keywords: rhythm, meter, entrainment, pulse, motion patterns, motion capture

1. Introduction

Catching the correct or intended basic pulse is fundamental to the production and perception of all rhythms with a meter. This pulse can be more or less directly articulated in the sounding rhythm of the music, but it remains vital to understanding the corresponding groove. If one fails to catch it, the groove may change character completely, or simply fall apart.

That the pulse is not always clear, or even present, in the sound points to the fact that the feeling of pulse actually emerges in the meeting of sound and listener. This organizing principle, as well as the phenomenon of musical meter understood as a matrix of heavy and light beats, have thus since long been acknowledged by music theorists as rising from endogenous, psychological processes (see, for example, Cooper and Meyer, 1963). Generally speaking, the experience of musical rhythm relies on the interaction between sounding rhythmic events and reference structures induced in and used by the listener to make sense of the sounds. This interaction has been approached under different guises. In the pioneering work of Eric Clarke (1985; 1987), which was based on, among others, Ingmar Bengtsson and Alf Gabrielsson’s (1983) theorizing and empirical investigations of systematic variations of durations in rhythm, it is conceptualized as a relationship between structure and expression. In folk music it has been seen as syntax versus process (Kvifte, 2004), and in jazz studies, such as for example Prögler’s classic study of swing grooves (1995), it has been conceptualized as

1 participatory discrepancies (Keil, 1995) from a presumed norm. As discussed in Danielsen
2 (2006), such non-sounding schemes are used (reactively) to predict and evaluate actual
3 sounding events. Whatever its guise, this interaction's crucial relevance to the experience of
4 rhythm is today a widely accepted premise in the musicological, ethnomusicological, music-
5 theoretical, and psychological strands of research. Interestingly, neuroscientists have now also
6 started to identify its underlying neural mechanisms (Fujioka et al., 2009; Nozaradan et al.,
7 2011; Snyder & Large, 2005).

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11 For the genre-confident listener, musical rhythm normally carries with it several
12 implications for reference structures, which might vary from a basic pulse, to a grouping of
13 the beats of such a pulse (the time signature), to various levels of subdivision. However, in
14 addition to what might be regarded as more or less 'universal' perceptual schemes, rhythm in
15 music also activates structures that are specific to the culture or musical genre, or even one
16 particular realization of the genre in question. Experiencing rhythm may thus involve a wide
17 variety of internal reference structures that are not part of the sound but instead *virtual*
18 mechanisms suggested by the sound (Danielsen, 2010a). Regardless, they remain basic to the
19 experience of rhythm, and a given rhythm will in fact morph into a different rhythm if it is
20 experienced with a different reference structure as the starting point. This phenomenon has
21 been labeled *metric malleability*, which refers to "the property by which many melodic or
22 rhythmic patterns may be heard in more than one metric context" (London, 2012: 99).¹ In this
23 sense, such virtual aspects are a real part of rhythm, "as though the object had one part of
24 itself in the virtual" (Deleuze, 1994, p. 209; see also Danielsen, 2006, chapter 3).

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35 The perceptual counterpart to the basic beats of the music—in the literature termed
36 'regulative beat' (Nketia, 1974), 'subjective beat' (Chernoff, 1979) or 'tactus' (London, 2012)
37 and here referred to as the *internal beat*—is fundamental to the experience of groove-based
38 music. It is typically used for conducting music (hence the alternate name *tactus*) and is also
39 the pulse expressed in foot tapping and other forms of time-keeping music-related body
40 motion (Su and Pöppel 2012). The psychological aspects of the internal beat have been
41 theorized and researched using both an internal clock model (Povel & Essens, 1985) and more
42 dynamic approaches (Desain & Honing, 2003; Large & Jones, 1999; London, 2012). In the
43 present study, we rely on the latter approach, and in particular on the theory of entrainment

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¹ Whereas London uses the term *rhythm* to denote the musical stimulus and meter for structuring perceptual schemes, we use rhythm to denote the *interplay* between the sound (the musical stimulus) and the non-sounding reference structures at work in the perceptual process, among them meter, stylistic figures, and other reference structures used to make sense of the sounds. Accordingly, we see the meeting of sound and listener as constitutive for experienced rhythm.

1 and dynamic attending as developed by Mari Riess-Jones and her collaborators (see, for
2 example, Jones, 1976; Jones & Boltz, 1989; Large & Jones, 1999; Jones, 2004).

3 Research into music-induced, spontaneous body motion indicates that layers of the
4 music's metric structure are associated with patterns of periodic motion (Toiviainen et al.,
5 2009; Toiviainen et al., 2010). The aim of this study is to investigate changes in the listeners'
6 body motion in relation to changes in the micro-rhythmic design of the beats of the basic
7 pulse in the tune 'Left & Right' by D'Angelo (*Voodoo*, 2000). We begin with a brief
8 presentation of the theory of dynamic attending. Then we theorize the response to the change
9 in the micro-rhythmic design of the beats from part 1 to part 2 of the tune, using previous
10 analytical work on the micro-rhythmic relationships in the tune (Danielsen, 2010b) and the
11 theory of dynamic attending as our points of departure. Finally, we report on a motion capture
12 experiment aimed at examining listeners' changes in body motion.

21 *1.1. Internal Beat as Dynamic Attending*

24 The theory of dynamic attending relies on key concepts from work on visual attention, such
25 as expectancy, attentional capture, and attentional focus, which are combined with theories of
26 resonance in dynamic systems to address attentional processes accompanying events with a
27 complex time structure, such as music. The theory rests on two assumptions—first, the
28 existence of internal oscillations in the perceiver, named *attending rhythms*, and second, the
29 fact that the external event's rhythm 'drives' these attending rhythms (Large & Jones, 1999,
30 p. 123). Attending or internal rhythms conform to how biologists conceive of rhythm—that is,
31 as a periodic process or so-called self-sustaining oscillation. This generates the periodic
32 activity that is referred to as *expectation*. Contrary to a grid point in memory code, for
33 example, the expectation in a dynamic attending system is an active temporal anticipation;
34 unlike a fixed clock, then, the attending rhythm can, when coupled to an external rhythm,
35 adjust to (or *entrain*; more on this below) and eventually synchronize with that rhythm. Such
36 a relationship is also robust in terms of perturbations, as the attending rhythm may adapt its
37 period to systematic changes in the external events (Large & Jones, 1999, p. 124).

38 When synchronized with the external rhythm, the attending rhythms point to where in
39 a repeated cycle a salient event is likely to occur, which can be advantageous in many
40 contexts. This attentional focus is conceived of as the result of a process whereby attentional
41 energy is allocated over time (Jones, 1976). Particularly interesting in a musical context is
42 how this transforms the attendant expectation from a point in time (as in a notational grid) to a
43 pulse of attentional energy that may have different shapes and also extends in time. Generally,
44 the theory postulates that attentional focus increases (that is, the pulse narrows) as

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synchronization improves, and decreases (the pulse widens) as synchronization degrades.² As Large and Jones point out, the concept of attentional focus might explain why a given deviation is more likely to be noticed when attention is highly focused (has a narrow pulse) than when it is broadly focused (has a wide pulse). In their theory, they assume that the pulse starts flat and then narrows as synchronization is achieved. In relation to the music that will be discussed shortly, we would add that the attentional span is a dynamic aspect that adapts to the features of the external rhythmic events—and, not least, that it can change over time.

Dynamic attending's salient *adaptability* to the environment also evokes recent applications of the theories of ecological perception (Gibson, 1986) to music (Clarke, 2005), particularly in relation to the way attending rhythms can adjust to changes in external rhythmic events through a process of entrainment. Entrainment arises in coupled systems, because coupling exerts a force that pulls two rhythms toward a synchronous relationship (Large & Jones, 1999, p. 127). In principle, there are two instances when entrainment processes are likely to occur: (1) when an attending rhythm is coupled to an external rhythm, and (2) when a perturbation in the external rhythm has taken place. Both are relevant for music perception. Moreover, in contrast to processes that take place between two flexible rhythms that are reciprocally adaptive—like Huygen's clocks or the interpersonal entrainment among musicians in a band—entraining to the beat of recorded music through listening or dancing is a one-way process, or an instance of *asymmetric entrainment* (Clayton et al., 2004).³ As with entraining to environmental processes (for example, the alternation of day and night), the individual cannot in such cases influence the entraining rhythm but is forced to adjust to externally set conditions. In modeling such entrainment processes, Large and Jones introduce the parameter 'coupling strength' as well as the notion of an 'attractor'. Coupling strength represents the amount of force exerted on the attending rhythm by the external event, and an attractor is a frequency toward which the system is drawn through coupling. In mutual entrainment processes, the attractor frequency might lie somewhere in between the two initial frequencies. When entraining to recorded music, however, the asymmetry in the process means that particularly salient periodical rhythmic events in the music will work as the attractor. The standard Western metrical matrix of accents (Lerdahl & Jackendoff, 1983) will usually make some beats 'heavier' than others (beat 1 is heavier than beat 3, which, in turn, is

² For the mathematical model comprising this process, see Large & Jones, 1999.

³ Himberg (2014, p. 25) suggests using *synchronization* for such asymmetric entrainment, reserving the term *entrainment* itself for the case of two-sided or mutual synchronization. In the present article, however, we use entrainment to refer to the processes of change linked with adjusting to an external rhythm, whether fixed or not, and synchronization to refer to the result of such entrainment processes.

1 heavier than beats 2 and 4, and so on). In addition, accent patterns that are typical of a
2 particular genre or style, such as, for example, the snare drum on beats 2 and 4 of a backbeat
3 groove or the hi-hat or ride cymbal pattern in a swing groove, are likely candidates, and it is
4 reasonable to believe that such recurring events are used by the listener (that is, in her
5 attending rhythms) in the process of synchronizing with the music.
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8 9 10 *1.2. Entraining to Change in the Beats of the Basic Pulse: The Case of D'Angelo's 'Left &* 11 *Right'* 12

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14 'Left & Right' from the album *Voodoo* (Virgin 2000), written by the American singer,
15 composer, and musician D'Angelo and co-produced by D'Angelo and Ahmir 'Questlove'
16 Thompson, has become a neo-soul classic due in part to its experimental groove. The tune
17 starts out relatively straightforwardly, with a syncopated guitar and percussion part (what we
18 will refer to as the 'guitar layer') that implies a clear regular pulse of quarter notes (part 1).
19 However, when the rhythmic layer comprised of bass drum/bass guitar and snare drum, in the
20 following referred to as the 'drum kit layer', enters the sound (part 2), the trouble starts,
21 because this rhythmic layer positions the internal beat considerably earlier in time than what
22 has, up to this point, been presented as the norm by guitar and percussion.
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26 Measurements in the amplitude/time representation of the groove reveal that the
27 'glitch' or discrepancy measured as inter onset interval (IOI) between the two rhythmic layers
28 in part 2 of the song is considerable: approximately fifty-five ms on the downbeats (beats 1
29 and 3) of the basic one-bar-long rhythmic pattern (4/4 meter), and approximately eighty ms
30 on the offbeats (beats 2 and 4)—that is, between 8 and 12 percent of a quarter note in the
31 song's tempo (92 beats per minute [bpm]; see Fig. 1). The clash between the two beat
32 positions is less striking on the downbeats, thanks to the slower attack time of the sound and
33 hence less precise onsets of the bass drum and bass guitar. On the offbeats, however, the
34 sharp attack of the syncopated guitar, which structurally strikes a sixteenth note ahead of the
35 beat, is far too close to the equally sharp attack of the snare drum on the beat. Put differently,
36 the virtual or "structural" distance is one 16th note, whereas the actual distance is close to one
37 32nd note. This introduces the groove's characteristic 'tilt'. Overall, the discrepancies between
38 the beat positions of the guitar layer and the drum kit layer are well above the just noticeable
39 differences for music both in strict time and in rubato performance (Clarke, 1989; Friberg &
40 Sundberg, 1995). They are also stable throughout the tune (Danielsen, 2010b).
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1 We will now hypothesize three different experiential phases of this groove. The first
2 corresponds to part 1 of the song (the introduction). The second is the transition following the
3 entrance of the drum kit layer, when the perceiver adjusts to the new micro-rhythmic design.
4 The third, part 2, covers the experience of being fully synchronized with these changes in the
5 groove. While the transition starts at a very specific point in the music, namely with the
6 entrance of the drum kit layer, it will end at different times for different listeners, depending
7 upon, among other things, one's stylistic 'insider' knowledge and one's degree of familiarity
8 with the song (for genre-confident listeners, that is, the transition phase might be barely
9 noticeable).

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17 *Part 1:* Part 1 consists of sharp percussive sounds that form an easily comprehensible and
18 stable rhythmic pattern that clearly indicates the basic rhythmic figures as well as the time
19 signature of the song (4/4; see Fig. 2).

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23 **[Insert Figure 2 here.]**

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27 Due to the distinct percussive character of the instruments used (rhythm guitar and shaker),
28 the internal beat can be rendered as a series of points in time to which the different rhythmic
29 layers appear congruent. The combination of shaker on all eighth notes with accents on the
30 quarter-note beats, and the unambiguous syncopated sixteenth notes before the offbeats
31 facilitates the listener's prompt synchronization of attentional rhythm with the 4/4 meter of
32 the groove. Hence, both strong period and strong phase coupling arise between the listener
33 and the groove. In accordance with the assumptions of the theory of dynamic attending, high
34 coupling strength generates strong and specific expectations regarding the continuation of the
35 groove, leading the listener's perceptual apparatus to allocate a narrow, high-peak pulse of
36 attentional energy that corresponds to the expected pulse location of the target musical event.

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45 *Transition:* When the drum kit layer enters the sound, a perturbation occurs. This is because
46 the bass guitar/bass drum (downbeats) and snare drum (offbeats) work together to position the
47 new internal beat significantly ahead of the guitar layer. The same phase mismatch happens
48 every time the pattern is repeated and the tempo remains the same. The phase discrepancy is
49 most striking on the offbeats, because the snare drum stroke is quite early compared to the
50 beat previously implied by the syncopated guitar (see Fig. 3).

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57 **[Insert Figure 3 here.]**

1 The somewhat ‘seasick’ or unstable feel that follows the entrance of the drum kit layer can be
2 explained by how these repeated perturbations initiate a process of forced phase resetting,
3 attenuating the precise positioning of the tactus and causing a decrease in the strength of the
4 coupling between the groove and the listener. The transition phase, again, will vary in length
5 depending on the listener.
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10 *Part 2:* In time the seasick feeling goes away and the groove is experienced as having a more
11 rolling feel. This is because the listener has now adjusted to the mismatch between the locus
12 and shape of the allocated attentional energy (a rather narrow pulse on the beat position
13 suggested by the guitar) and the new micro-rhythmic design with multiple onsets of each beat.
14 According to the theory of dynamic attending, when synchronization decreases, attentional
15 focus widens. It may thus be envisioned as changing from the narrow peak induced by the
16 sharp, point-like beats of part 1 to a more saddle-like shape or ‘beat bin’ that is wide enough
17 to encompass the multiple onsets of each beat (see Fig. 4).
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28 With the notion of a ‘beat bin’ we mean the perceived temporal width of a beat according to
29 the musical context. Multiple onsets of a particular beat falling within the boundaries of the
30 perceived beat bin will be heard as merging into one beat, whereas onsets falling outside these
31 boundaries will be heard as belonging to another category—namely, that of ‘not part of the
32 beat’ (Danielsen, 2010b, p. 29-32).
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36 When one is fully synchronized with part 2 of the groove, one’s attentional focus has
37 widened due to the altered design. The phase discrepancies are no longer experienced as
38 perturbations, because the widened attentional focus encompasses the differing beat positions
39 at the micro level—the phase discrepancy is simply absorbed in the beat bin, and the coupling
40 between the external events and the internal attending rhythms thus returns to a stable state. It
41 might, however, now be a looser and more flexible coupling than that which arose from the
42 sharp attentional focus induced by the intro of the song. Moreover, because of the particularly
43 striking multiple onsets at beats 2 and 4, the frequency of the attentional rhythms that
44 corresponds to the groove’s level of quarter notes (92 beats per minute) might be considerably
45 weakened, whereas synchronization at the half-note level gains ground. Given the strong
46 action-perception coupling (see, for example, Large, 2000; Chen et al., 2008; Repp, 2005), we
47 would expect that the motion responses to the groove would change accordingly.
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2. Material and Methods

2.1. Hypotheses

Based on the above analytical and theoretical discussions, we designed an experiment aimed at capturing changes in body motion patterns in response to the altered micro-rhythmic design of the beats forming the pulse in part 2 of the groove. We hypothesized the following change in motion patterns from part 1 to part 2:

- a) Increase in *quantity of motion* due to higher average sound-pressure level. This is based on the general ecological assumption that there is a connection between bodily effort and sound loudness (see, for example, Clayton & Leante, 2013; Iyer, 2002; Leman, 2008 (chapter 7); Shove & Repp, 1995; and Van Dyck et al., 2013).
- b) Decreased *synchronization* of the motion pattern corresponding to the quarter-note pulse, and increased synchronization to the half-note pulse (as a consequence of the salient phase discrepancy between the multiple onsets of beats 2 and 4).
- c) Increase in the micro-level temporal *spread of pulse positions* in the motion pattern, reflecting looser phase coupling and widening of the attentional focus.

2.2. Participants

Twenty participants (13 female, 7 male, median age 28 [21 35]) were recruited to the experiment. The majority of the participants reported to be amateur (45%) or semi-professional musicians (40%), while only one participant was a non-musician. They described varied musical backgrounds, most of which fell within groove-based genres. When asked about their engagement with dancing, around 40% of the participants stated that they move to music occasionally, while 35% dance regularly. The music stimuli used in the experiment were unfamiliar to 55 % of the participants.

2.3. Procedure, Stimulus, and Task

The experiment was carried out in the motion capture lab at the Department of Musicology, University of Oslo, a black box of about 60 m². Each recording session comprised four participants at a time, standing with their backs to one another so that they could not see anyone else during the experiment. The participants held a stick resembling a percussion instrument in their hand, with the palm facing upward. Two reflective markers were placed on each side of the stick. In addition, reflective markers were attached to each participant's head and knees. A picture of the experimental situation is shown in Fig. 5.

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5 The participants were asked to move the stick naturally in their hand to the pulse of the music.

6 Five sound clips were mixed into one continuous sound file in the following order:
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- 8 i. Test clip consisting of a looped excerpt of a different track from the *Voodoo* album.
9 This clip was used to acquaint the participants with the setup and the task.
- 10 ii. Looped four-bar excerpt of part 1 of the original groove.
- 11 iii. The groove in its original version played from the beginning, including the transition
12 from part 1 to part 2.
- 13 iv. Looped four-bar excerpt of part 2 of the original groove.
- 14 v. Control track consisting of metronome clicks with the same beats per minute as the
15 original groove.
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21 Each sound clip lasted for thirty seconds and was followed by ten seconds of silence, as
22 illustrated in Fig. 6. The complete sound file was played once for each group of participants.
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30 In the following analysis, we focus on the difference in motor response between
31 sound clip ii (part 1) and sound clip iv (part 2). In addition to change in the micro-rhythmic
32 design of the basic beats, that is, from single to multiple onsets of the beats, the average
33 sound-pressure level increases significantly from part 1 to part 2—from -34.2 dB to -16.5 dB
34 average RMS power of both channels, with an RMS window of 200 ms and normalized such
35 that a sine wave with maximal intensity 1 would correspond to 0 dB. More instruments are
36 also added in part 2, but the structural complexity of the basic groove (micro-timing excluded)
37 does not increase, because the drum kit and the bass generally articulate the same basic
38 quarter-note pulse (see Figs. 2 and 3 above). In fact, this basic pulse might be said to be even
39 more explicit in part 2, thanks to the fact that here every beat is marked by a heavy drum
40 sound (bass drum or snare drum), whereas in part 1 the beats are played by a light percussion
41 instrument (shaker) and only implicated by the syncopated guitar. This quarter-note pulse is,
42 however, now counterbalanced by the rhythmic variation provided by the lead vocal and the
43 multiple onsets of beats in part 2.
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53 Summing up, the main differences between stimuli ii and iv (parts 1 and 2) are (a) an
54 increase in the complexity of the micro-rhythmic design—that is, multiple onsets on all
55 quarter-note beats in part 2; (b) an increase in sound level; (c) an increase in the number of
56 instruments articulating the basic pulse; and (d) the addition of rhythmic variation through the
57 lead vocal.
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2.4. Apparatus

The motion of the reflective markers on the bodies of the participants was recorded at 100 Hz with a nine-camera optical motion capture system from Qualisys (Oqus 300) using the accompanying software (QTM 3.7). The musical examples were played over a 2.1 Genelec sound system using a custom-built Max/MSP patch that ensured synchronization with the motion capture data.

3. Results

The final motion capture (mocap) data set consists of a total of 100 markers (20 participants, 5 markers per participant). Since the participants primarily moved the hand holding the stick, we only included data from one of the stick markers in our further analysis. Here, we decided to use data from the outward-pointing marker on the sticks, because there was only one dropout in this marker set (some of the inward-pointing markers suffered from visual occlusion). The data were analyzed using the MoCap Toolbox for Matlab (Burger & Toiviainen, 2013), which contains a collection of analysis functions aimed specifically at studying music-related motion. In our study we used the function for calculating the cumulative distance traveled (*mccumdist*) for each marker to estimate the *quantity of motion*. The amplitude spectrum of the mocap time series (*mcspectrum*) was used to identify *motion periodicities*, measuring the strength of the frequencies corresponding to the quarter- and half-note beats of the music. In addition, time-series plots of motion data were used to identify where motion along the vertical axis changed direction (the turning points). The turning points corresponding to quarter-note beats in the music were then used to capture the *spread in the temporal location of pulse* in the motion data. In a study of conductor's gestures, Luck and Sloboda (2009) showed that acceleration peaks were the main cues for beat location and synchronization. Thus the spread in pulse positions was also investigated using acceleration peaks from the motion data, that is, maxima and minima of acceleration corresponding to beats in the music. All statistical analyses were performed using SPSS version 21 (IBM, Inc.).

3.1. Quantity of Motion

Subtracting the start and end values of the cumulative distance for each part, we arrived at the net distances traveled during part 1 and part 2. Data from one of the participants was excluded from further analysis because of missing data points. Paired-samples t-tests were then performed to determine the difference in mean cumulative distance between part 1 and part 2.

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On average, participants moved significantly more to part 2 ($M=15\,866$ mm, $SE=2127$) than to part 1 ($M=11\,175$ mm, $SE=1174$, $t(18)=3.9$, two-tailed $p<0.005$).

The plot of the quantity of motion (QoM) for the right stick marker for all participants (see Fig. 7) shows that, overall, the QoM is lowest in response to the metronome at the end of the session (v). This means that the increase in motion from part 1 (ii) to part 2 (iv) most likely did not come as a consequence of the latter simply being positioned later in the sequence of clips. Moreover, it is also clear from the plot that in clip iii, which included the transition from the introduction to the main groove, there is an increase in QoM that is related to the change in the groove.

[Insert Figure 7 here.]

We also tested whether there was a systematic relationship between the measured QoM and the responses to the questions about ‘interest in music’ or ‘relationship to dancing’ from the questionnaire. However, no such significant relationship was found.

3.2. Motion Periodicities

We conducted a qualitative evaluation of the motion spectra for the right stick marker for each participant in both part 1 and part 2. The motion spectrum depicts the relative strength of the frequencies (in Hz) in which the participants moved. The participants were divided into three groups, ‘excellent’, ‘marginal’, and ‘poor’, based on whether there were clear peaks in their motion spectrum or not. The category ‘excellent’ contains the motion spectra in which there is no doubt about the ability to synchronize with the beats of the music, that is, the beat-relevant amplitudes are at least the double of any of the surrounding periodicities. The category ‘poor’, on the other hand, contains spectra in which there are no clear beat-relevant amplitude peaks at all. The category ‘marginal’ refers to those spectra where there is a peak at one or more frequencies that relate to the beats in the music, but where these peaks are only marginally higher (less than double amplitude) than the surrounding periodicities. (For examples of the different categories, see Fig. 8.) Fifteen participants (75%) were considered to have excellent frequency peaks in their motion patterns for both part 1 and part 2 or excellent for one part and marginal for the other part. For the remaining five participants (25%) one or both of their performances fell within the category “poor”, that is, the spectral analysis showed that the participant failed to produce a stable periodic motion of sufficient amplitude to indicate whether or not they perceived the internal beat of the music. These participants were omitted from further analysis. The distribution in the categories is illustrated in Table 1. Of the five participants who were omitted from further analysis, three participants

1 showed stable, periodic motion ('excellent' frequency peaks) when moving to the metronome
2 (v), whereas the spectra of the remaining two showed poor frequency peaks also when
3 moving to the metronome's isochronous series of clicks (see Table 2).
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17 The results for the fifteen participants with clear frequency peaks in their motion spectra
18 (excellent/excellent and excellent/marginal) revealed the following motion periodicities:
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- 21 • The median for the slowest frequency peak in both parts was 0.77 Hz (46 bpm),
22 which represents periodic motion at the half-note level.
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- 24 • The median for the next slowest peak in both parts was 1.53 Hz (92 bpm), which
25 represents periodic motion at the quarter-note level.
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27 This means that most participants synchronized with the groove at the half- and quarter-note
28 levels. In order to identify significant differences in periodic motion between parts, we
29 measured the amplitude of the frequency peaks corresponding to the music's half- and
30 quarter-note levels for the fifteen participants who had clearly moved in synchrony with the
31 groove. Paired-samples t-tests were performed for the pair Part2_halfnote versus
32 Part1_halfnote and Part2_quarternote versus Part1_quarternote. On average, the peaks
33 corresponding to the half-note level in the participants' motion spectra were significantly
34 stronger in part 2 (M=29 596, SE=4825) than they were at that level in part 1 (M=12 614,
35 SE=3143, $t(14)=3.388$, two-tailed $p<0.05$). For quarter notes there was no significant
36 difference between part 2 (M=23 975, SE=5960) and part 1 (M=22 915, SE=3143).
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46 *3.3. Spread in the Temporal Location of Pulse*

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49 Next we wanted to investigate the spread in the participants' temporal location of their
50 internal beats using the vertical motion of the stick in the participants' motion response. The
51 vertical motion was considered particularly important for synchronizing with the groove,
52 because of the stick's similarity to a shaker, a percussion instrument that is usually moved
53 rhythmically up and down in accordance with the perceived pulse of the music. We identified
54 the position's trough and peak points, that is, the points in time in which the position changed
55 direction from down to up and vice versa. The assumption here is that such turning points in
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1 periodic motion express the participant’s perceived temporal location of the corresponding
2 beat in the music. Thirteen of the participants exhibited clear vertical periodic motion in
3 synchrony with the beats in the music for all beats in both part 1 and part 2 (regular vertical
4 motion) and were included in the analysis. The remaining participants did not show regular
5 beat-related, vertical motion or had too many missing data points for the right stick marker
6 within the chosen analysis window (irregular vertical motion). For examples, see Fig. 9.
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11 **[Insert Figure 9 here.]**
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15 In this part of the experiment we were interested in finding out whether the ‘beat bin’
16 increased from part 1 to part 2. We operationalized ‘beat bin’ as the temporal spread of
17 turning points in the motion response corresponding to quarter-note beats for the 13
18 participants that made regular motion. First, thirty-two turning points in the motion patterns
19 (corresponding to 4 beats/bar x 8 bars) in part 1 and thirty-two in part 2 were identified for
20 each participant. Second, we calculated the difference between participants’ turning points
21 and the corresponding quarter-note beats in the music. In part 2 there are multiple beat onsets,
22 so in order to allow for comparisons we chose the quarter-note positions implied by the guitar
23 layer in each part’s first bar (see Figs. 1, 2 and 3) as the reference for our measurements in all
24 8 bars in both part 1 and 2. Descriptive statistics showed that the nominal distance from the
25 earliest to the latest mean of turning points increased by 126 milliseconds from part 1 to part
26 2. The median of the means of the turning points moved 25 milliseconds earlier in time, that
27 is, in the direction of the drum kit layer’s positioning of the internal beat.
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37 Because the nominal distance between the earliest and latest mean of turning points is
38 susceptible to outliers, we decided to also use the *variability* of turning points as a measure
39 for temporal spread (i.e., the width of the beat bin). The standard deviation (SD) of the 13
40 means of turning points increased from 67 to 90 milliseconds from part 1 to part 2. To test
41 whether there was an increase in the variability at the individual level, we calculated the
42 standard deviation (SD) of turning points for each participant in parts 1 and 2 respectively,
43 and performed a paired-samples t-test for the difference in mean SD for the pair part 2–part 1.
44 On average, the test showed a significant increase in temporal spread (SD) at the individual
45 level from part 1 ($M=0.0317$, $SE=0.0028$) to part 2 ($M=0.0425$, $SE=0.0040$, $t(12)=2.479$, two-
46 tailed $p<0.05$).
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53 We then performed the analysis above on acceleration peaks and troughs, that is, the
54 maxima and minima of the acceleration corresponding to each of the quarter-note beats in the
55 music, to see if this would produce any different results from the positional turning point
56 analysis. Using the MoCap Toolbox the vertical acceleration was calculated for the 13
57 subjects that were included in the analysis. We then applied a mathematical function for
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1 identifying the peaks and troughs in the graph, i.e., the minimum and maximum points of the
2 acceleration curve. The motion capture data were smoothed using the *mcsmoothen* function
3 and the beat-related peaks and troughs manually selected. Peaks/troughs located more than
4 0.20 seconds away from its corresponding beat-related turning point were not considered
5 related to the same beat. The distance to the quarter-note reference of the guitar layer was
6 then measured. Descriptive statistics showed that the nominal distance from the earliest to the
7 latest mean of acceleration points increased by 83 milliseconds from part 1 to part 2, while the
8 median location moved 42 milliseconds earlier in time. The standard deviation of the 13
9 means increased from 79 to 94 milliseconds from part 1 to part 2. We then calculated the
10 standard deviation (SD) of the acceleration points for each participant in parts 1 and 2, and
11 performed a paired-samples t-test for the difference in mean SD for the pair part 2
12 (M=0.0561, SE=0.0076) – part 1 (M=0.0525, SE=0.0073). The test yielded no significant
13 result ($t(12)=0.398$, two-tailed $p=0.698$).
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23 **4. Discussion**

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26 The results of the analysis show that the participants moved more to part 2 than to part 1 of
27 the groove. This was anticipated (hypothesis a) because there is a considerably higher average
28 sound level (and thus more energy) in part 2. This finding is supported by a recent
29 experimental study by Van Dyck et al. (2013), which shows that the quantity of body motion
30 increases with the loudness of the sound. However, the result can also partly be caused by an
31 increase in the motion-inducing quality of the groove between part 1 and part 2, as a
32 consequence of the micro-rhythmic design of the latter. Unfortunately, this cannot be
33 systematically studied from our current data set.
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40 Regarding the expected changes in the periodicities with which the participants
41 synchronized to the music (hypothesis b), we found a significant increase in the periodic
42 motion corresponding to the half-note level in part 2 as compared to part 1, but no significant
43 difference at the quarter-note level. This means that the increase in the quantity of motion
44 from part 1 to part 2 was mainly attributable to the addition of periodic motion corresponding
45 to the half-note level. The increase in motion at this slower periodicity accords with the
46 prediction derived from the analytical and theoretical discussions above and might be
47 explained as a relative weakening of synchronization at the quarter-note level as a
48 consequence of the salient multiple onsets of beats 2 and 4 (offbeats). It might also be
49 associated with the general tendency toward producing higher-order resonances when
50 increasing the input energy in non-linear oscillator systems (see Large, 2008).
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58 The quantity of motion at the quarter-note level did not nominally decrease for the
59 different parts, which indicates that the participants were still able to maintain
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synchronization at this frequency. This means that the rhythmic events at the quarter-note level are probably still ‘regular enough’, to paraphrase London (2012, p. 121–123), to work as an attractor for the internal rhythm. According to London, if a pulse layer becomes too non-isochronous, the differing beat lengths will cease to be perceived as variations of the same pulse. They will rather form two different categories of beats—for example, short and long—that are in turn judged as qualitatively different. The fact that participants still synchronize with the groove at the quarter-note level in part 2 thus indicates that, despite the considerable phase discrepancy between the differing onsets of the beat, they perceive the quarter-note level as isochronous also in this part. This in turn supports the initial hypothesis that the perceptual response to part 2 is characterized by a wider attentional focus and a weaker phase coupling, even though the overall period coupling remains intact. In this respect the current study is different from previous synchronization studies using perturbation or distractor paradigms (for a review, see Repp & Su, 2013). The multiple onsets forming the beats in part 2 are a stable and repeated feature of the groove, thus creating a different entrainment problem than do isolated perturbations.

Based on the analytical observation that there are multiple suggestions for beat positions in part 2, we expected an increase in the temporal spread of turning points and acceleration peaks in the motion response from part 1 to part 2 (hypothesis c). The distance from the earliest to the latest mean of turning points increased by 126 milliseconds from part 1 to part 2, which means that there was a nominal widening of the beat bin. Furthermore, our results showed a significant increase in the temporal spread (standard deviation) of turning point positions in the motion response corresponding to quarter-note beats in the music from part 1 to part 2 at the individual level when using the guitar layer as reference for both parts. This we interpret in support of the hypothesized increase in beat bin, but it might also reflect a general uncertainty of the exact perceived pulse location.

A complementary explanation might be that the perceived reference for quarter-note beats has changed from the guitar layer to the drum kit layer. The fact that the median of means of turning points moved 25 milliseconds earlier in time, that is, toward the drum kit layer’s positioning of the internal beat and further away from the guitar layer, points in this direction. There is also another aspect that supports this explanation. In contrast to the quarter-note pulse implied by the guitar layer, in which beats 1 and 3 are longer than beats 2 and 4, the drum kit layer is almost isochronous. Interestingly, if using the drum kit layer’s positioning of the quarter-note beats as reference for the measurements of turning point positions in the motion response in part 2, the standard deviation is on average lower (mean $SD=0.0396$) than when using the guitar layer as reference (mean $SD=0.0425$). This means that the introduction of multiple onsets did not necessarily increase the temporal spread of the turning points at the individual level. As such, this finding concurs with the results from a

1 recent study by Elliott et al. (2014), in which participants took advantage of the more reliable
2 (isochronous) layer in producing a single beat estimate when synchronizing with beats with
3 multiple onsets produced by one highly isochronous and one less isochronous layer. In
4 general, they found that participants were able to integrate considerable phase offsets (up to
5 100 milliseconds). Also in our study, we find that the median of means of turning points
6 moves in direction of the more reliable (isochronous) drum kit layer (rather than switch to it).
7 In a tapping study using chords with multiple (i.e., double) onsets as stimulus, Hove et al
8 (2007) also found that inter-tap-interval variability was generally *not* degraded by the
9 presence of multiple onsets (onset asynchrony = 30 milliseconds) in the pacing sequence. On
10 the contrary, participants with musical training tapped with less variability when the chords
11 contained multiple onsets. Taking all this into consideration, the question regarding a possible
12 increase in the standard deviation of turning points within participants from part 1 to 2
13 remains open. However, several aspects point in the direction of the drum kit layer having a
14 profound influence on the perceived beat positions, 'moving' them earlier in time, that is, the
15 temporal locations of the perceived beats are drawn away from the guitar layer in direction of
16 the drum kit layer.

17
18 Also for acceleration points, the nominal distance from the earliest to the latest mean
19 increased significantly (83 milliseconds) from part 1 to part 2. However, the results of the
20 statistical tests showed no significant increase in standard deviation at the individual level.
21 This might be explained by the relationship between turning points and acceleration points
22 (peaks/troughs) being different in our study compared to Luck and Sloboda's investigations
23 of conductor's gestures (2009). In a recent audio-visual synchronization judgment study, Su
24 (2014) found that the extent to which peak velocity positions for the auditory beat coincided
25 with turning point positions depended upon the kind of motion used as visual cues. When the
26 motion was a bouncing ball, the positions indicated by velocity and position data coincided.
27 However, when the motion was human bouncing, the beat points of the velocity data and the
28 position data did not coincide, that is, the peak velocity points were considerably earlier in
29 time than the turning point positions. It should also be noted that there were differences in the
30 procedure for identifying points in the motion response between turning points and
31 acceleration points. Whereas the turning points were manually identified, the acceleration
32 points were identified computationally, which might have influenced the results.

33
34 Summing up, the results provide support for the hypothesized connection between the
35 change in the micro-rhythmic design of the basic beats of a groove and the change in the
36 motion patterns of subjects' entrainment to this groove. In short, we found that when the
37 multiple onsets of beats are introduced in part 2, a slower pulse becomes a significant
38 additional level of entrainment. Participants still synchronize with the faster pulse, but the
39 temporal locations of the perceived beats are drawn towards the added onset. The findings
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1 were predicted using the theory of dynamic attending (Large & Jones, 1999), and the
2 experimental results support this theory, as well as the resonance theory for beat and meter
3 perception in humans (Large & Kolen, 1994; Large, 2008).
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5 We also found an association between increase in sound level and increase in the
6 quantity of motion. In future studies it would be interesting to pursue the potential role of
7 *microtiming* in generating larger and/or more motion. We also wish to investigate whether
8 there is a significant increase in the variability of the turning points' means, which would
9 reflect an increase in the systematic variation of the phase of the turning points amongst
10 participants. Furthermore, we seek a way to conduct systematic investigations of the
11 entrainment process as such. The design of the present experiment allowed for a comparison
12 of the conditions before and after the change in the groove, but it remains to develop an
13 experimental design focused on the process of change as it happens.
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25 The authors wish to thank the reviewers for extraordinary thorough and constructive
26 feedback.
27

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Discography

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Table 1. Qualitative evaluation of frequency peaks in spectra of motion periodicities for parts 1 and 2 (all participants).

N	%	Part 1/Part 2
7	35	Excellent/Excellent
8	40	Excellent/Marginal
1	5	Marginal/Marginal
3	15	Marginal/Poor
1	5	Poor/Poor

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Table 2. Qualitative evaluation of frequency peaks in spectra of motion periodicities for part 1, part 2, and metronome (omitted participants).

Subject	Part 1/Part 2	Metronome
1	Marginal/Poor	Poor
2	Marginal/Marginal	Poor
3	Poor/Poor	Excellent
4	Marginal/Poor	Excellent
5	Marginal/Poor	Excellent

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Figure 1
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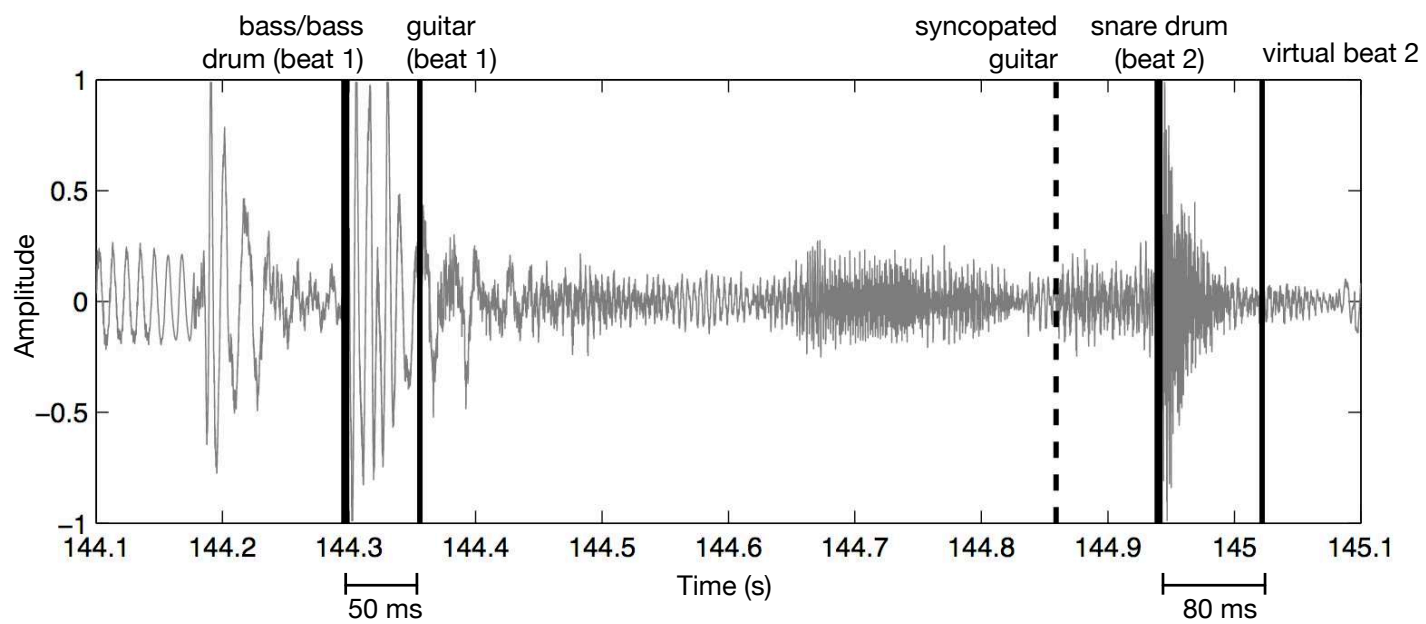


Figure 2

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Percussion



Guitar

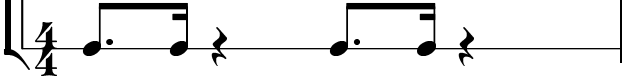


Figure 3

[Click here to download Figure: figure3.ps](#)

Percussion

Musical staff for Percussion in 4/4 time. It shows a sequence of notes: quarter, quarter, quarter, quarter, eighth, eighth, eighth, eighth, quarter, quarter. A triplet bracket is over the last three notes. A double bar line is at the end.

Guitar

Musical staff for Guitar in 4/4 time. It shows a sequence of notes: quarter, quarter, quarter, quarter, quarter, quarter, quarter, quarter. Triplet brackets are over the first and fifth notes. A double bar line is at the end.

Snare drum

Musical staff for Snare drum in 4/4 time. It shows a sequence of notes: quarter, quarter, quarter, quarter, quarter, quarter, quarter, quarter. Triplet brackets are over the first and fifth notes. A double bar line is at the end.

Bass drum

Musical staff for Bass drum in 4/4 time. It shows a sequence of notes: quarter, quarter, quarter, quarter, quarter, quarter, quarter, quarter. Triplet brackets are over the first and fifth notes. A double bar line is at the end.

◁ = early ▷ = late

Figure 4
[Click here to download Figure: figure4.eps](#)

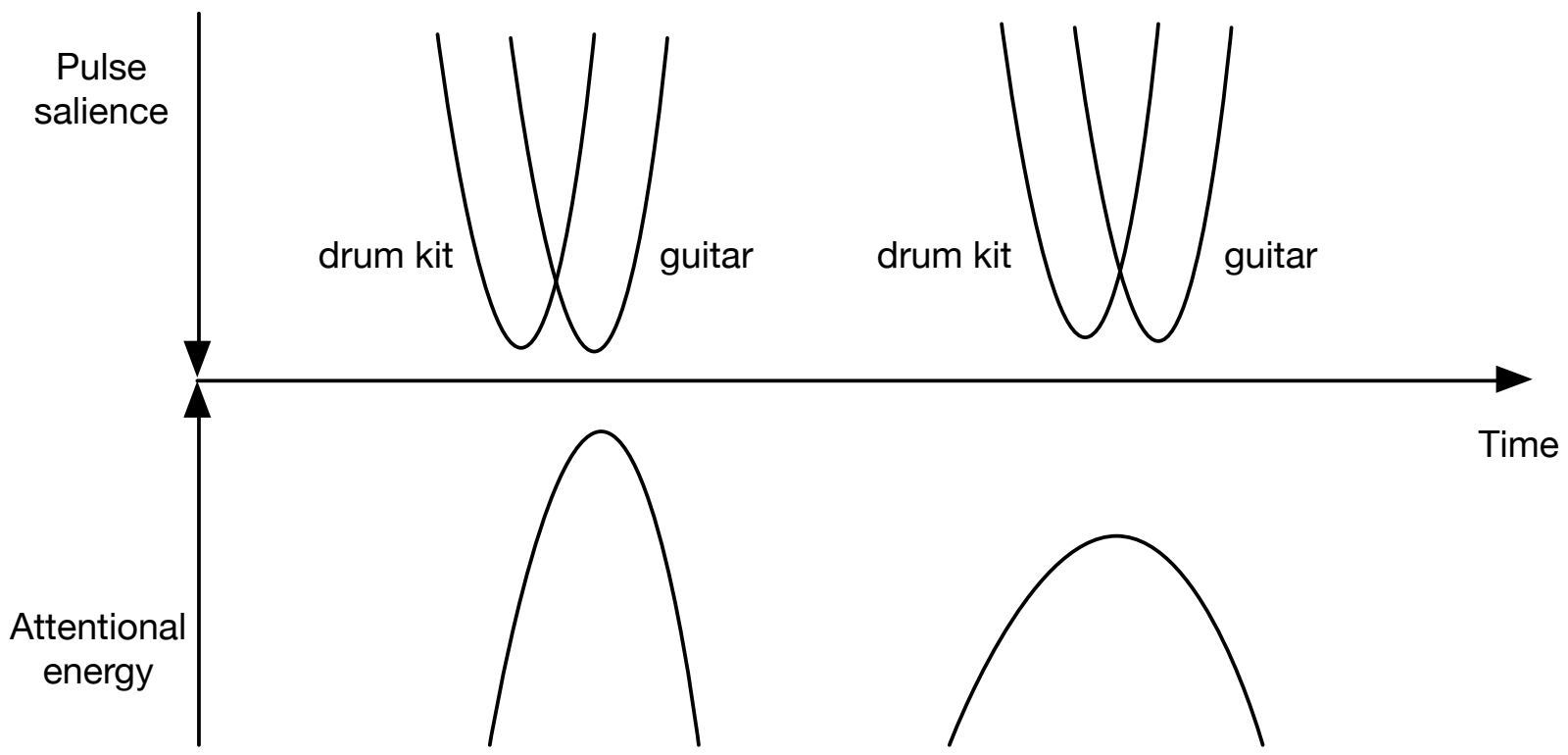
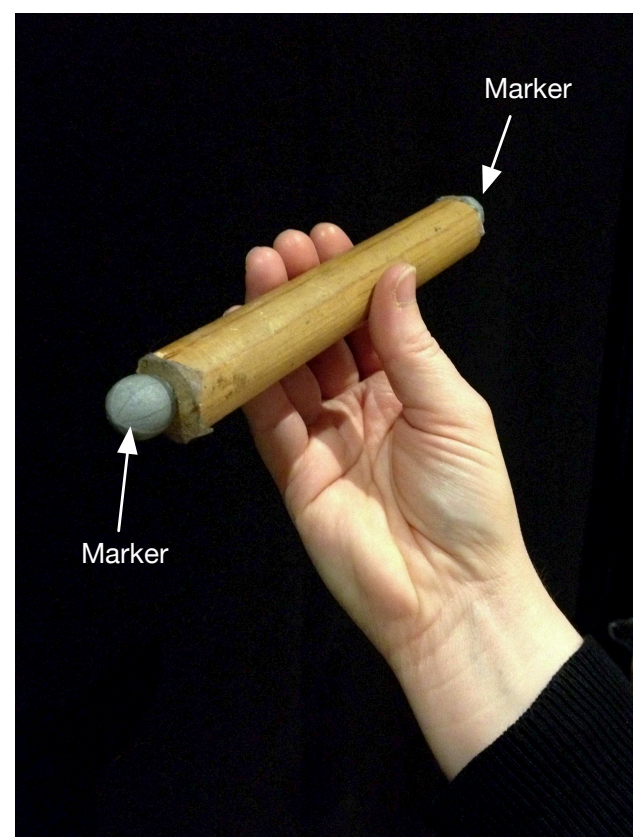
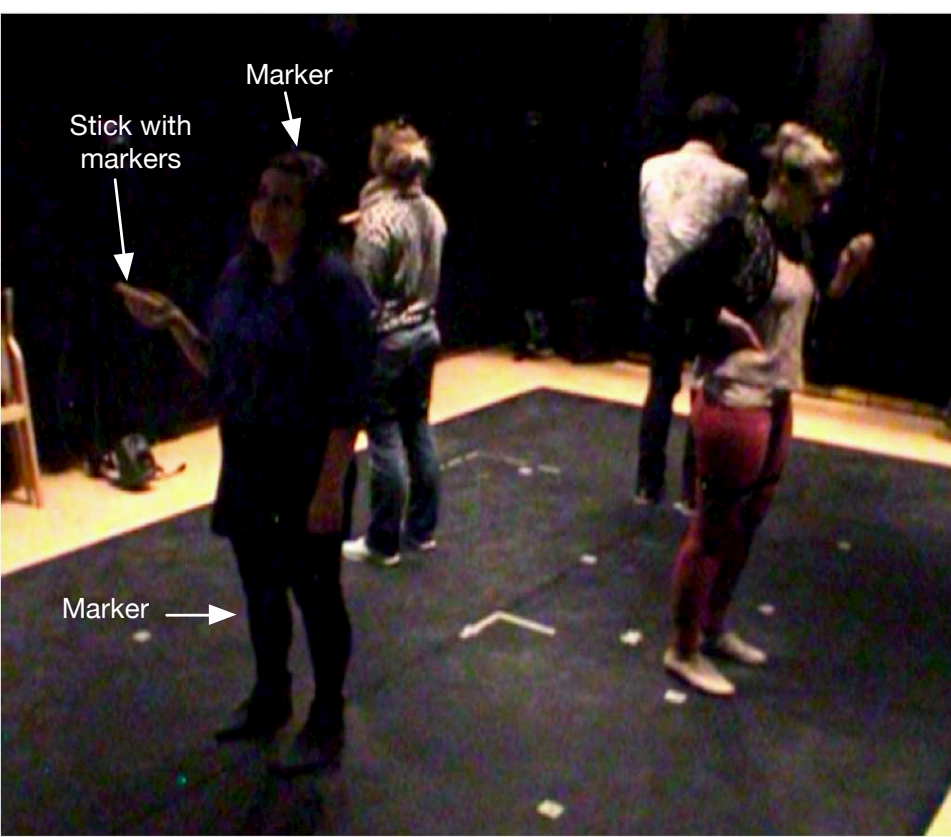


Figure 5
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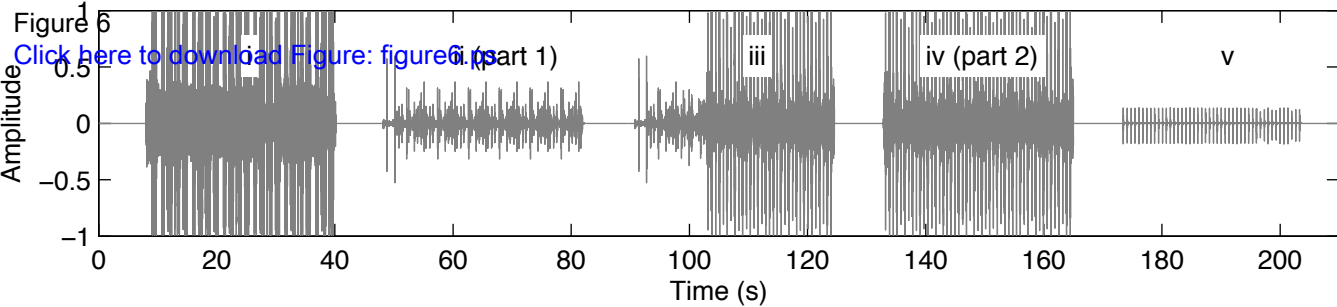
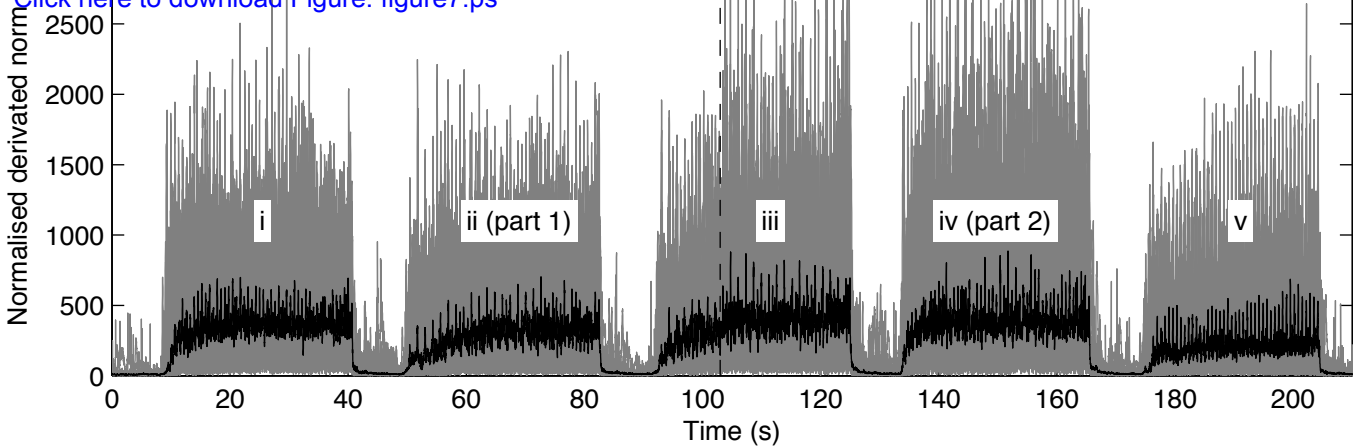
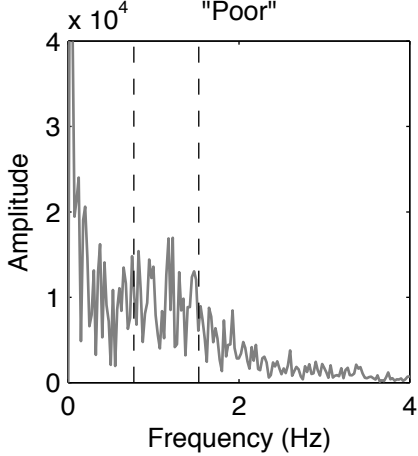
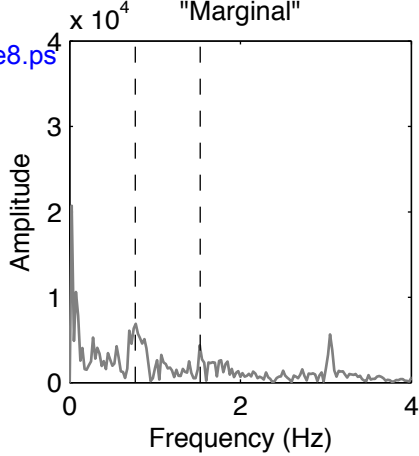
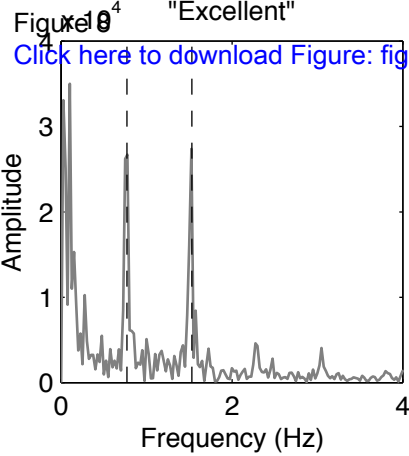


Figure 7

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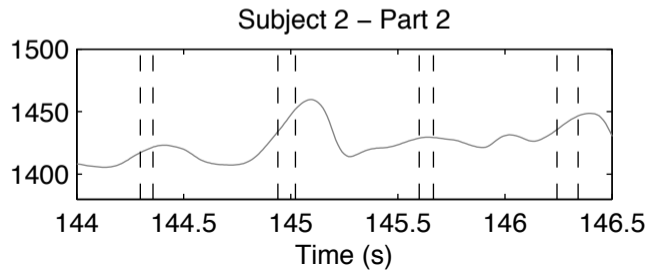
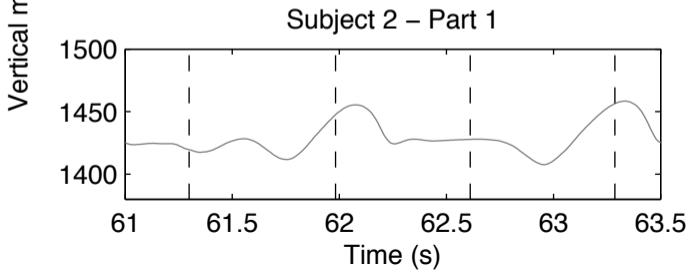
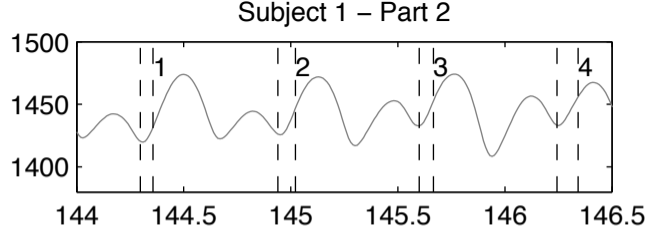
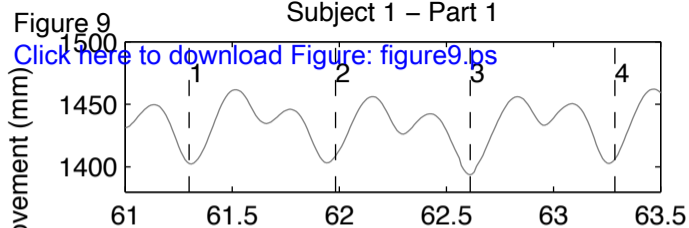


Figure 1. Waveform display (amplitude/time) of bar 14 of ‘Left & Right’. Actual beat onsets are indicated by black vertical lines. The virtual beat position at beat 2, one sixteenth after the actual onset of the syncopated guitar, is indicated by stippled line. The time refers to the placement of the clip within the sound file prepared for the motion capture experiments (see below).

Figure 2. Basic rhythmic structure of guitar layer in Part 1.

Figure 3. Basic rhythmic structures of guitar layer and drum kit layer in part 2. The quarter-note pulse implied by the guitar is located fifty to eighty ms later in time than the pulse implied by the bass drum and snare drum kit.

Figure 4. Transition to part 2, from the mismatch between a point-like expectation and actual rhythmic events (left) to a widened attentional focus—a ‘beat bin’ that encompasses the multiple onsets (right).

Figure 5. The experimental setup in the motion capture lab, with the four participants standing back-to-back with sticks in their hands (left) and a close-up of a stick with reflective markers attached (right).

Figure 6. Waveform representation of the musical examples (amplitude/time): (i) test clip (looped excerpt of a different track from the *Voodoo* album) (ii) looped four-bar excerpt of part 1 of the original groove, (iii) original groove (thirty seconds from the beginning of the song, including the transition from part 1 to part 2), (iv) looped four-bar excerpt of part 2 of the original groove, (v) metronome clicks in the same tempo as the original groove.

Figure 7. Combined plot of the motion of stick markers for the five sound clips for each of the 20 subjects individually (gray line) and median value of all subjects (black line), calculated as the first derivative of the vector length (norm) of the motion. The entrance of drum kit layer in the original groove (stimulus iii) marked by the dotted line.

Figure 8. Examples of spectra showing typical cases for the different periodicity categories. Clear frequency peaks (excellent), partly visible peaks (marginal) and no obvious peaks (poor).

Figure 9. Examples of regular (subject 1) and irregular vertical motion (subject 2). Estimated beat positions corresponding to beat onsets in the music are indicated by stippled lines.