博士論文

Effect of groove on movement induction, sensorimotor synchronization, and group synchronization

（身体動作喚起、感覚運動同期、集団同期に対するグルーヴの影響）

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Chapter 1:
Introduction

1.1 Music and body movement

Music has existed for at least 35,000 years (Conard et al., 2009) and has consistently been one of the most important elements of culture for human beings, enriching our daily lives and playing an important role in various societies. In fact, upon frequently observing people sitting and listening to music in today's society, one might understandably assume that music is enjoyed through our ears specifically. However, various studies have pointed out that there is a strong connection between music and our bodies (Levitin et al., 2018), and furthermore, that one engages with music using their entire body (Keil and Feld, 1994). The behavior of audiences during rock, hip-hop, or electronic music concerts are typical examples. Participants move, dance, and synchronize their bodies to the rhythms they hear in music. In fact, there are various musical styles that coexist with specific dances, such as flamenco, salsa, samba, waltz, and too many more to mention, corroborating the insight that there is a tight connection between music and the human body.

As stated above, there are countless cases in which one can observe the relationship between music and the body. In addition to such observations and personal experiences, numerous empirical studies have confirmed and detailed a tight link between the two. In addition to choreographed dances to particular types of music, another example of observable action highlights a listener's behavioral responses towards music. When people listen to music, they tend to move their body in such ways as tapping their feet, nodding their heads, or swaying their whole bodies (Janata et al., 2012). Such responses seem to be learned over time during the process of human development, but it is reported that 3-4-month-old infants already exhibit behavioral responses when exposed to music or rhythms (Fujii et al., 2014). In addition, it has been shown that when 5-24-month-old infants hear music, it not only induces random body movements, but also spontaneous rhythmic movement (Zentner and Eerola, 2010). This means that we develop responses to music using our entire bodies and that we show rhythmic movement at a relatively early stage of development. The fact that music induces body movement is also supported by several studies in neuroscience using fMRI, EEG, and MEG. It is not surprising that brain areas related to movement become activated when we play an instrument (Chen et al., 2008b) or tap along with a rhythm (Chen et al., 2006; Kung et al., 2013) because in such cases, we can observe these movements. What is intriguing is that, in addition to this fact, areas of the brain related to movement—such as the primary motor area (Stupacher et al., 2013), supplementary motor area (Bengtsson et al., 2009; Grahn and Brett, 2007), basal ganglia (Grahn and Brett, 2007; Grahn and Rowe, 2009), premotor cortex (Bengtsson et al., 2009; Chen et al., 2008a), and cerebellum (Bengtsson et al., 2009)—become activated when people simply listen to music or rhythms without making any visible movements (Merchant et al., 2015). This indicates that listening to music facilitates movement, or more specifically, action, within the body.

Not only does music encourage listeners to move their bodies, but it also influences the synchronization of such movements to the rhythm. A previous study has shown that, in addition to stimulating spontaneous body movement, such as that of the head, hand, foot, or trunk, music also seems to encourage one to synchronize their movement to the rhythm playing (Janata et al., 2012). As previously stated, spontaneous rhythmic movement can be seen in infants 5-24 months old; however, the ability to synchronize one's movement to a rhythm appears to be acquired later, as infants up to 24 months old have not been shown to have this ability (Zentner and Eerola, 2010). In fact, an experiment using tapping reported that a group of 4-5-year-old children showed lower ability to tap constantly as compared to a group of 6-7-year-olds (McAuley et al., 2006). These studies indicate that the neural networks between the auditory cortex and motor areas are at least partly formed at an early stage of development, and people start synchronizing their movements to music as they sufficiently develop control of their motor skills around the age of 5-6 years.

Furthermore, it has been shown that music not only induces body movement and causes this movement to become synchronized to the rhythm, but it also affects the behavior of synchronization in terms of modulating the strength of entrainment, and elicits various behaviors depending on the structural hierarchy of the rhythm (Burger et al., 2013, 2014, 2018; Kilchenmann and Senn, 2015; Levitin et al., 2018; Toiviainen et al., 2010; Van Dyck et al., 2013; Witek et al., 2017).

As seen above, music engages with our bodies in a variety of ways, such as inducing body movement, enhancing the synchronization of body movement with music, and eliciting variety in the types of movement. Here, I want to emphasize the fact that the trigger, which provides all these important connections, is the sensation of wanting to move our body when listening to music. The aspect of music that makes people want to move is called "groove" (Stupacher et al., 2013). In the current study, I focus on the concept of groove, which is a fundamental aspect of music that associates music with the human body. In the next section, I will briefly review the relevant studies on the subject of groove.

Before continuing to the review, I will briefly explain several musical terms appearing in this thesis. Music consists of three elements: melody, harmony, and rhythm. As the current thesis focuses on the rhythmic attributes of music, I will only describe certain musical terms related to rhythm. First of all, *rhythm* is defined as "the systematic grouping of musical sounds, principally according to duration and periodical stress" (Rhythm, n.d.), and the musical feature that provides the foundation for rhythm is called *beat*, which is the "basic pulse underlying mensural music, that is, the temporal unit of a composition" (Beat (i), 2001). When the quality of a beat changes through loudness, pitch, or timbre modification, *meter* is created, which is defined as "the grouping of beats (in jazz most often four, three, or two) into a recurring pattern (the bar) defined by accentuation" (Meter, 2003). *Tempo* is also another important aspect of rhythm, which occasionally refers to "the 'time' of a musical composition, but more commonly [is] used to describe musical speed or pacing" (London, 2001). Tempo is usually described by a unit called *beats per minute* (bpm), which shows the number of beats included in one minute. *Groove*, therefore, is regarded as an aspect of music that is created by the combination of musical features related to rhythm such as beat, tempo, accent, and meter.

1.2 Studies of groove

The question of what, exactly, groove is can be divided into three areas of inquiry making up studies of groove conducted thus far. They can be described by the question each line of study asks. The first question is, "What is the concept of groove?" The second question goes beyond a definition, asking, "Which musical features contribute to creating groove?" The third question asks, "What are the functions of groove?" The study of groove began to address the first question in the 1990s. Then, in 2000s, psychological studies started to address the second question, and only recently has the third question been addressed by behavioral and neuroscientific studies. Henceforth, this thesis will review previous groove studies according to these three questions.

1.2.1 What is the concept of groove?

Studies in musicology and ethnomusicology

The study of groove first emerged in the realm of musicology and ethnomusicology. Charles Keil is regarded as the father of groove studies. He first proclaimed the importance of slight rhythmic deviations, which he called "participatory discrepancies" for groove (Keil, 1995; Keil and Feld, 1994). For instance, in the performance of jazz music, the beats of the bass and drums are not completely synchronized; rather, there is a slight deviation between them. In addition, in the performance of drums alone, there is a deviation between the timing of the snare drum and the bass drum. Keil stated that this slight rhythmic deviation is one crucial factor in eliciting groove. Iyer (2002) also focused on the importance of rhythmic deviation, which he called "expressive microtiming" (or microtiming). According to Iyer, having a constant beat is the most important factor in groove, and a slight rhythmic deviation from the quantized timing, which enables rich expression similar to controlling the intensity and pitch of sound, is also crucial for groove. The importance of microtiming for groove has been supported by other studies (e.g., Zagorski-Thomas, 2007). However, some researchers believe that strictly isochronous beats may create groove, as well (Fitch, 2016). Others have even suggested that microtiming is detrimental to groove (Merker, 2014). The way microtiming affects groove is, in fact, one of the greatest interests of groove studies. Empirical studies addressing this issue will be reviewed in the next section.

Studies in psychology

In the 2000s, empirical studies of groove began to be undertaken in the field of psychology. Guy Madison is the pioneer of the psychological study of groove. In 2006, he conducted a cognitive experiment in which participants were asked to rate music excerpts from various geographic areas (i.e., African, African American, Indian, Latin American, Scandinavian, and South European) with 14 rated items, including "groove." By conducting a factor analysis, he revealed that the words "rapid," "bouncing," and "intensive" were related to groove. Although Madison stated that he could not extract important aspects of groove from his study, he claimed that groove is an element that is not dependent on music genre or style (Madison, 2006).

Next, Kawase and Eguchi (2010) followed these studies with their own, first conducting a survey on how the concept of groove is recognized in Japan. Then, they asked participants to define groove. The results showed that participants' definitions included words and phrases related to body movement, such as "my body is moving spontaneously" and "dancing inducing." In addition, through a cognitive experiment in which participants subjectively rated the degree of groove of several musical excerpts, it was revealed that their ratings of groove showed a high correlation with the ratings of items such as “nori is good,” “blithe,” “you feel a sense of unity,” “up-tempo,” and “your body feels rhythm.”

Janata et al. (2012) also asked participants to provide a definition for groove. The results showed that words related to rhythm and movement—such as “move,” “beat,” “rhythm,” and “dance”—most frequently appeared in their definitions, indicating that groove is a concept commonly related to body movement. In addition, the researchers presented several sentences explaining groove and asked participants to rate how much they agreed with these explanations. The sentence, “The groove depends on the extent to which the music makes you want to move,” obtained the highest rating. This result suggests that groove is widely recognized as an aspect that elicits body movement, and considering these results, most research has applied “an aspect of music that makes you want to move” as the standard definition of groove.

1.2.2 What musical features contribute to creating groove?

After 2010, psychologists started to investigate musical features that contribute to creating groove. Tempo is the musical feature that has been most frequently investigated in previous studies. However, there are two contradicting conclusions about the relationship between tempo and groove. Three studies have concluded that tempo has no significant relationship with groove (Davies et al., 2013; Madison, 2006; Madison et al., 2011), while another two studies concluded that music with a fast tempo obtains higher groove ratings (Janata et al., 2012; Kawase and Eguchi, 2010). Therefore, the relationship between groove and tempo remains an issue for study. Solving this problem is one of the current study’s aims. I will review these studies more in detail in Chapter 2.

Microtiming (or participatory discrepancies), introduced in the last section as a slight rhythmic deviation (Butterfield, 2006), has also been investigated with empirical studies. This is due to microtiming being regarded as one of the most important constituents of groove (Iyer, 2002; Keil, 1995; Keil and Feld, 1994; Madison et al., 2011; Naveda et al., 2011). In fact, microtiming has been shown to affect the behavior of people dancing to music (Kilchenmann and Senn, 2015). However, in contrary to theoretical and behavioral notions, studies including cognitive experiments have reported that microtiming is not necessarily an important factor for groove (Senn et al., 2016), that microtiming does not affect the rating of groove (Madison et al., 2011; Senn et al., 2018), or that microtiming may even have a detrimental effect on the rating of groove (Davies et al., 2013), all together indicating that perfectly quantized rhythm obtains the highest groove rating. Investigating the relationship between groove and microtiming by solving the problems in the aforementioned studies is another aim of the current study. I will review these studies more in detail and state their shared problem in Chapter 3.

Effects of musical features other than tempo and microtiming on groove have also been investigated. One example is the effect of rhythmic complexity, or the degree of syncopation. Two studies, one using drum breaks as stimuli (Witek et al., 2014), and the other using piano melodies (Sioros et al., 2014) have investigated the effect of syncopation and provided the same conclusion that rhythms with a moderate degree of syncopation obtain the highest ratings for groove. This indicates that rhythms that are neither too simple nor too complex elicit the highest ratings for groove.

Other than these musical features, it is reported that beat salience (Madison et al., 2011), event density (Madison et al., 2011), RMS (root mean square) curve (Stupacher et al., 2016), spectral flux (Stupacher et al., 2016), and the low frequency of bass sounds (Stupacher et al., 2016) affect the rating of groove, as well.

1.2.3 What are the functions of groove?

Does groove induce body movement?

So far, I have focused on groove studies based on cognitive experiments in which participants subjectively rated the groove of stimuli such as musical excerpts and drum breaks. The second question to investigate is, “What are the functions of groove,” especially in relation to body movement. Janata et al. (2010) were the first to address the relationship between groove and body movement, beginning with the important issue of whether groove actually contributes to increased body movement, because, as stated, groove is defined as an element of music encouraging body movement and is widely recognized as related to listeners’ movements. In order to investigate this question, they recorded the movements of participants while listening to musical excerpts with video cameras and analyzed them. The study revealed that music with a high groove rating increased spontaneous movement as compared to music with low or moderate groove ratings. In addition, a study using TMS revealed that music with a high groove rating increased the activation of the primary motor area in musicians compared to music with low or middle groove ratings (Stupacher et al., 2013). Their results prove that groove is not merely a subjective feeling that encourages body movement, but is actually responsible for inciting spontaneous body movements, as supported by neurophysiological evidence.

Effect of groove on body movement

In addition to the function of groove inducing body movement, groove is shown to affect body movement in a variety of forms. One important function of groove to be mentioned is its effect on the synchronization of body movements to music. By conducting a tapping experiment with musical excerpts, Janata et al. (2010) revealed that tapping to music with high groove ratings is subjectively less difficult than tapping to music with low or moderate groove ratings. In addition, they revealed that the degree of synchronization increases when tapping to music with high groove ratings. In another study, it was reported that music with high groove ratings enhanced the degree of synchronization when walking while listening to music (Leow et al., 2014). These results indicate that groove enhances the synchronization of body movements to music.

Another study also revealed that groove affects quietly standing while listening to music. It is reported that when standing still while listening to music, music with high groove ratings enhanced the synchronization of participants' movements to music at high frequencies, and music with lower groove ratings enhanced synchronization to music at low frequencies (Ross et al., 2016).

As seen above, in addition to inducing body movement, groove performs the function of affecting the degree of synchronization of the body's movement to music (Janata et al., 2012; Leow et al., 2014).

1.3 Purpose of the thesis

In this thesis, I address two questions: "Which musical features contribute to creating groove," and, "What are the functions of groove?" More specifically, I investigate: (1) which musical features affect the rating of groove (Studies 1 and 2); (2) does groove also contribute to enhancing the synchronization of body movements to sound sequences (Study 3); and (3) the effect of groove on group synchronization.

In Chapter 2, I will focus on an experiment in which I investigated the relationship between groove and tempo, which has been shown to have contradictory conclusions (Janata et al., 2012; Madison et al., 2011). More specifically, I conducted a cognitive experiment investigating the hypothesis that there is an optimal tempo for groove.

In Chapter 3, I will focus on another cognitive experiment, in which I investigated the effect of microtiming on groove, which has not been shown to have a positive effect on groove in previous studies (e.g., Davies et al., 2013), despite microtiming being regarded as one of the most important factors for groove by musicians and scholars (e.g., Iyer, 2002). In this study, I aim to overcome the problem of previous studies by applying drum breaks with randomly fluctuating onset timing following Gaussian distributions.

In Chapter 4, I will focus on an experiment in which I conducted a sensorimotor synchronization task in order to investigate whether groove contributes to enhancing the synchronization of body movement with music. As a previous study showed that beat salience increases the rating of groove (Madison et al., 2011), and that accent increases beat salience (Parncutt, 1994), I investigate the effect of accent in order to determine the effect of groove on sensorimotor synchronization.

In Chapter 5, I will focus on a pseudo-music concert experiment in which I investigated the effect of groove on group synchronization. As previous studies revealed that groove enhances the synchronization of body movements to music (Janata et al., 2012), I hypothesized that groove also enhances synchronization between people. Therefore, I conducted a pseudo-music concert experiment in which participants served as an audience and were allowed to behave freely, in order to see if groove enhances group synchronization.

In Chapter 6, I will first summarize the results of each study, and then I will discuss the implications of the current study on groove. Particularly, I aim to discuss the functions of groove other than inducing body movement, and the functional importance of groove in relation to the evolution of music.

1.4 Definition of groove

As formerly stated, most psychological, behavioral, and neuroscientific research defines groove as “an aspect of music that makes you want to move,” and there is indeed strong agreement on this definition (Sioros et al., 2014). However, before simply applying this definition in the current study, I will briefly summarize the definition of groove used in previous studies.

To be precise, there are three different definitions of groove. The first definition is "an aspect of music that makes you want to move" (Janata et al., 2012; Stupacher et al., 2013, 2016). The second definition is an element that "evokes the sensation of wanting to move some part of the body" (Madison et al., 2011). The third definition involved "wanting to move some part of the body in relation to some aspect of the sound pattern" (Davies et al., 2013; Madison, 2006; Sioros et al., 2014). The first two definitions could be regarded as similar, assuming that "an aspect of music" is omitted from the second definition. The third definition describes groove as not only inducing body movement, but further implicates such movement as related to a sound pattern. In the current study, I decided to apply the first definition in order to prioritize using the most commonly accepted definition.

Although there is a strong agreement on the definition of groove (Sioros et al., 2014), it is indeed still a vague concept. I will reconsider the definition of groove in a general discussion.

1.5 Significance of the study

First of all, the main significance of this study is to enrich our understanding of music. The study of music has a long history, but mostly has focused on the melodic attributes of music. Recently, however, interest in the relationship between music and the human body has grown, and the importance of our bodies in enjoying music has been reported in various studies, especially in the fields of psychology and neuroscience. Important findings include that people spontaneously move their body when listening to music (Janata et al., 2012), and that areas of the brain related to movement increase activation when simply listening to music (Bengtsson et al., 2009; Grahn and Brett, 2007). As represented by these examples, studies focusing on the relationship between music and the body have provided new insights into the quality and function of music. As formerly stated, the trigger engendering this relationship is the sensation of wanting to move when listening to music, or the main theme of this thesis—groove. Therefore, revealing the quality and functions of groove will offer new knowledge on the relationship between music and the body, and eventually lead to a deeper understanding of music. Especially, revealing the quality and functions of groove will contribute to unveiling the evolutional significance of music. Overall, this insight will help explain why music has been a persistent part of culture for such a long time.

Furthermore, results of the current study may potentially be applied to discussions of several practical usages. First, the results could be informative for musicians and composers. It is crucial that musicians create groove in the field of popular music, especially for jazz, funk, and R&B. Particularly, one of the most important tasks for drummers and bassists is to encourage listeners to "feel" the groove. Therefore, unfolding which musical features contribute to building groove may be beneficial in deciding how and what to play. In addition, the current study could also be informative for composers. One important function of composers of musical genres such as electronic dance music, trance, and hip-hop is to make the audience dance. Thus, the current study may also offer possibilities in different ways of composing music to provide the highest level of groove.

In addition, the results of the current study may also be applicable to rehabilitation. Ample studies have shown that auditory information, including music, is an effective element in kinetic therapy (Chen et al., 2016) and cognitive therapy (Hiroharu et al., 2014). Especially, it is reported that auditory stimuli are useful in rehabilitating patients of stroke and Parkinson's disease to walk (Lim et al., 2005; Nascimento et al., 2015). Therefore, revealing which musical features contribute most to inducing body movement and enhancing movement synchronization may be applicable to such rehabilitation efforts.

Chapter 2:
Optimal tempo for groove

2.1 Introduction

2.1.1 Musical features related to groove

Movements such as body sway, head nodding, and foot tapping frequently coincide with listening to music. The aspect of music that induces such bodily movement has been defined as groove (Davies et al., 2013; Janata et al., 2012; Leow et al., 2014; Madison, 2006; Madison et al., 2011; Pressing, 2002; Ross et al., 2016; Witek et al., 2017).

One big interest of groove studies is to reveal which musical features contribute to creating groove, and several studies have investigated this topic through cognitive experiments. Thus far, they have shown that musical features like beat salience (Madison et al., 2011), event density (Madison et al., 2011), tempo (Janata et al., 2012; Kawase and Eguchi, 2010; Madison, 2006; Madison et al., 2011), degree of syncopation (Sioros et al., 2014; Witek et al., 2017), RMS (root mean square) curve (Stupacher et al., 2016), and spectral flux (Stupacher et al., 2016) affect the rating of groove. Additionally, several studies have revealed that microtiming, which has been considered as an important characteristic for groove, does not contribute to the rating of groove (Madison et al., 2011), and may even decrease the rating of groove (Davies et al., 2013).

2.1.2 Groove and tempo

The musical feature that has been investigated most frequently in previous studies is tempo. Tempo is one of the most important elements of music. In fact, tempo affects the listener's perception of music in terms of expressiveness (Shaffer and Todd, 1994) and emotion (Gabrielsson and Lindström, 2010). As tempo has been shown to affect musical perception, several studies have investigated the relationship between groove and tempo. However, there is one crucial problem in that these studies have produced contradictory conclusions: the first is that there is no significant relationship between tempo and groove, and the other conclusion is that music with a faster tempo elicits a higher groove rating.

Madison et al. (2006) conducted a cognitive experiment using musiccal excerpts from various genres and revealed that the correlation coefficient between the rating of items “groove” and “fast” was not high (*r* = .28), although it was significant. Furthermore, they revealed that there was no significant correlation between the rating of “groove” and the actual tempo of musical excerpts. In addition, in a following study using musical excerpts from various genres (Greek, Indian, Jazz, Samba, and West African music), they revealed no significant correlation between the rating of groove and the tempo of any genre of music. These two studies suggest that there is no relationship between groove and tempo.

On the other hand, there are studies showing that there is a significant relationship between groove and tempo. By conducting a cognitive experiment using musical excerpts of rock and fusion, Kawase and Eguchi (2010) revealed that there is a significant positive correlation between the rating item “groove” and “up-tempo” (*r* = .41), and that there is a significant positive correlation between the rating of groove and the actual tempo of each excerpt (*r* = .84). Furthermore, Janata et al. (2012) showed that music with a fast tempo had significantly higher ratings of groove compared to a group of music with slow tempos through a cognitive experiment using musical excerpts from four different genres (folk, rock, jazz, and soul/R&B). Contrary to the former studies, these two studies indicate that music with a fast tempo tends to obtain higher groove ratings.

Studies investigating the effect of tempo on groove can be divided into two groups: one concluding that there is no significant relationship between groove and tempo (Madison, 2006; Madison et al., 2011) and one concluding that faster tempo elicits higher groove ratings (Janata et al., 2012; Kawase and Eguchi, 2010). These two conclusions seem to contradict each other, but considering the range of tempo applied in each study and postulating that there is an optimal tempo for creating groove would explain why two contradictive conclusions have emerged.

First of all, the range of tempo applied in those studies concluding that there was no significant relationship between groove and tempo, was 55-280 bpm (Madison, 2006) and 61-182 bpm (Madison et al., 2011). For instance, if there is an optimal tempo for groove at around 120 bpm, there would be an inverted U-shaped relationship between groove and tempo. If this was the case, a significant correlation would not be observed and this may account for the results of these studies. In addition, the mean tempo of the fast tempo group and the slow tempo group in the study, which showed a significant positive correlation between groove and tempo, were 90.8 bpm and 115.6 bpm, respectively (Janata et al., 2012). Therefore, it is possible that the reason the fast tempo group obtained higher groove ratings was because the mean tempo of this group was closer to the optimal tempo for groove, compared to the mean tempo of the slow tempo group. As seen above, hypothesizing that there is an optimal tempo for groove would explain the two contradictory conclusions shown by previous studies. This hypothesis is well supported by the indication that the tempo of music that obtained high groove ratings in Janata et al.'s (2010) study centered around 100 (± 10) bpm (Ashley, 2014).

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2.1.3 Body movement and tempo

Additionally, though not directly investigating the effect of groove, studies that investigated the relationship between body movement and tempo suggest that there is an optimal tempo for groove, or for inducing body movement. For instance, a study that analyzed the tempo list of music used by DJs reported that the distribution peak of tempo lied between 120-130 bpm, suggesting that an optimal tempo for inducing body movement lies around 120-130 bpm (Moelants, 2002). In addition, it is reported that people's preferred tempo for walking is 120 bpm (MacDougall, 2005), and that walking along with a beat becomes most synchronous when the tempo is 120 bpm (Styns et al., 2007). These results suggest that there is a tempo at which people can easily move the body, prompting body movement, and that this tempo is around 120 bpm. In addition to the findings of these behavioral studies, some neuroscientific studies support this idea, as well. For instance, a previous study revealed that the activation of basal ganglia is maximized when listening to rhythms with a tempo of 86-120 bpm (i.e., IOI is 500-700 ms). Furthermore, another study using fMRI revealed that listening to a rhythm with a preferred tempo activates the ventral premotor cortex, which is related to movement, more than listening to a rhythm with a non-preferred tempo (Kornysheva et al., 2010).

To summarize, these studies support the idea that there is an optimal tempo that induces body movement, or groove, and that it lies around 120 bpm.

2.1.4 Groove and the complexity of rhythm

Although there is an optimal tempo for groove, as stated above, it is possible that this optimal tempo differs among music styles or rhythmic patterns. In fact, previous studies have revealed that, in addition to tempo, the complexity of a rhythm (i.e., degree of syncopation) affects the rating of groove (Sioros et al., 2014; Witek et al., 2017). Witek et al. (2014) revealed that there is an inverted U-shaped relationship between the rating of the item, "I want to move my body," (i.e., groove) and the degree of syncopation by conducting a cognitive experiment using drum patterns with various degrees of syncopation as stimuli. This result indicates that a moderate degree of syncopation induces body movement the most (i.e., creates groove). Additionally, another study using piano melodies as stimuli provided the same conclusion, which is that a moderate degree of syncopation maximizes groove ratings. As the rhythmic pattern affects the rating of groove, it is possible that there is an optimal tempo for groove and, further, that it may be affected by rhythmic patterns.

2.1.5 Aims and hypotheses

In this study, a cognitive experiment was conducted using 30 drum breaks and the following two hypotheses were investigated: (1) there is an optimal tempo for groove, and (2) this optimal tempo differs among rhythmic patterns.

2.2 Methods

2.2.1 Ethics statement

All participants were informed as follows: their participation was voluntary; they were free to leave if they felt uncomfortable; and absence or withdrawal of participation provided no disadvantage for participants. Following a presentation with oral and written instructions, all participants agreed and signed a letter of consent.

2.2.2 Participants

Thirty-eight university students (21 female, 17 male) aged 18 -40 years (mean = 22.9, SD = 4.5) majoring in music at Tokyo University of the Arts participated in the study. The mean musical experience of the participants was 15.0 years (SD = 5.8). The groove ratings of three participants were removed because these individuals had missing responses or responded in a way suggesting that they did not understand the concept of groove, when answering the open-ended question, “What types of performance do you think are groovy?”

2.2.3 Stimuli

Thirty drum breaks were employed as stimuli. Each drum break consisted of hi-hat, snare drum, and bass drum sounds, which were synthesized using GarageBand (v. 6.0.5, Apple, Inc.). To create different types of stimuli, five different rhythmic patterns were used as bases for the drum breaks (Figure 2-1). Thirty drum breaks were created in consideration of the following criteria:

(1) The number of hi-hat, snare drum, and bass drum sounds used in each drum break was the same across all patterns, because an imbalance in the number of sounds in the drum breaks could affect the perceived complexity of the rhythm. Each stimulus consisted of eight hi-hat, two snare, and three bass drum sounds in one bar.

(2) To minimize potential causes of variance, only the position of the bass drum sound was manipulated to create different rhythmic patterns. The positions of hi-hat and snare drums were the same across each drum break.

(3) Each drum break had a different degree of syncopation, which was calculated according to a previous study (Witek et al., 2014). This index defines the degree of syncopation using the metrical salience of each note and the relative position of notes. The degrees of syncopation were 2, 11, 2, 13, and 15 for Patterns 1 through 5, respectively.

Each drum break was presented at six different tempi: 60, 75, 100, 120, 150, and 200 bpm. These tempi were chosen to fit within a natural musical tempo range, in accordance with previous studies. Each stimulus was 40 s long, including 3 s of fade out.

2.2.4 Procedure

The experiment was conducted in a soundproof room at Tokyo University of the Arts (Figure 2-2). Due to the room's capacity, the experiment was conducted in seven sessions, with three to eight participants in each session. Participants sat in a chair and listened to thirty drum breaks in random order, rating each stimulus on eleven items (Table 2-1) including, "Performance with high groove," using a seven-point scale (7 = strongly agree, 6 = agree, 5 = agree to a certain degree, 4 = neither, 3 = disagree to a certain degree, 2 = disagree, 1 = strongly disagree). Participants were instructed to rate how they felt about each given stimulus regarding these items.

All stimuli were presented via a loudspeaker (Genelec 8050A), 3.5 m from the closest seat, using iTunes. Before the experiment, two drum breaks not used in the experiment were presented for practice. During the experiment, participants were told to listen to each stimulus for at least one bar, and then start rating. Each trial was about 40 seconds long. The entire experiment lasted approximately 25 minutes.

2.2.5 Data analyses

Optimal tempo for groove

To investigate whether an optimal tempo for groove exists, linear and quadratic regression analyses were conducted employing groove rating as a dependent variable, and tempo as an independent variable. Then, the goodness of fit of the two models were compared by comparing the sums of squared errors (Kutner et al., 2004).

Comparison of the optimal tempo for groove among rhythmic patterns

Finally, to investigate whether the optimal tempo differed among rhythmic patterns, the distribution of the optimal tempo for each pattern was first provided using a Monte Carlo simulation (n = 50,000). Afterwards, the distribution for optimal tempo was compared between rhythmic patterns.

The distribution of optimal tempo was provided by two random variables of B and B^2 with known distributions, where B_c and $B^2{}_c$ are coefficients and SE_B and $SE_B{}^2$ are standard errors obtained from the quadratic regression model, and t_B, $t_B{}^2 \sim t$ (225). The definitions are as follows:

$B \sim B_c + SE_B\, t_B$

$B^2 \sim B^2{}_c + SE_{B2}\, t_B{}^2$

$bpm_{opt} = -B / 2B^2$

To investigate whether the distribution of optimal tempo differs among rhythmic patterns, the distribution of difference in the optimal tempo was provided using a Monte Carlo simulation (n = 100,000), and calculated the significance probability (two-sided).

2.3 Results

2.3.1 Optimal tempo for groove

The results indicated that the quadratic regression model fit significantly better than the linear regression model for all five patterns (ps < .01). In addition, the secondary coefficient of quadratic regression (B^2) showed a negative value and was statistically significant for all patterns (ps < .01). These results present an inverted U-shaped relationship between the groove rating and tempo, suggesting an optimal tempo for increasing groove. The optimal tempos for Rhythm Patterns 1 to 5 estimated from the quadratic regression model were 123.1, 126.4, 114.0, 110.6, and 106.9 bpm, respectively (Table 2-2).

2.3.2 Comparison of the optimal tempo for groove among rhythmic patterns

The result of the Monte Carlo simulation showed no significant difference in the distribution of optimal tempo between any rhythmic patterns.

2.4 Discussion

2.4.1 Summary of results

I conducted a cognitive experiment using 30 drum breaks (5 rhythm patterns × 6 tempi) as stimuli in order to investigate two hypotheses: (1) there is an optimal tempo for groove, and (2) the optimal tempo differs among rhythmic patterns. A linear regression analysis and a quadratic analysis were conducted, which showed that the quadratic regression model fit significantly better than the linear regression model, and that the secondary coefficient (B^2) showed a negative value for every rhythmic pattern. This result indicates that as hypothesized, there is an optimal tempo for groove. The optimal tempo for groove estimated from the quadratic regression model ranged from 107-126 bpm. Furthermore, a Monte Carlo simulation (n = 100,000) was conducted in order to investigate whether the optimal tempo for groove differs among rhythmic patterns. However, the results showed no significant difference in the optimal tempo between rhythmic patterns.

2.4.2 Comparing results to previous studies

As stated in the introduction, there have been two differing conclusions about the relationship between groove and tempo: (1) there is no significant relationship between groove and tempo (Madison, 2006; Madison et al., 2011), and (2) faster tempo elicits higher groove ratings (Janata et al., 2012; Kawase and Eguchi, 2010). The results of the current study can likely explain the reason why two different conclusions have been presented.

Studies that provided the first conclusion analyzed the relationship between groove and tempo by obtaining the correlation coefficient between the rating of groove and tempo. The tempo range of musical excerpts used in these studies were 55-280 bpm (Madison, 2006), and 61-182 bpm (Madison et al., 2011), respectively. The reason why they showed no significant correlation between the rating of groove and the rate of tempo is most probably due to the inverted U-shaped relationship between them, as well as the use of musical excerpts from a wide range of tempi as stimuli.

On the other hand, the study providing the second conclusion analyzed the data by comparing the mean groove rating of music between the slow tempo and fast tempo groups, showing that the rating was significantly higher in the latter group (Janata et al., 2012). The mean tempo of music used in this study was 90.8 bpm for the slow tempo group, and 115.6 bpm for the fast tempo group. This indicates that the reason why the fast tempo group obtained higher groove ratings is because the mean tempo for the fast tempo group was closer to the optimal tempo for groove as shown in the current study, which is around 107-126 bpm.

In addition, although the value does not completely coincide, the optimal tempo shown in the current study is close to the tempo of music that obtained high ratings of groove in Janata et al.'s (2012) study, which was confirmed by Ashley (2014).

2.4.3 Optimal tempo for body movement

The optimal tempo for groove, which is around 107-126 bpm, is in line with several previous studies investigating the relationship between tempo and body movement. First of all, it is worth mentioning that the tempo of music most frequently used by DJs lies around 120-130 bpm (Moelants, 2002), and this is because one role of the DJ is to make people move and dance. Taken with results of the current study, this indicates that DJs use tempo practically to encourage movement in the audience.

In addition, it is intriguing that the optimal tempo for groove is close to the people's preferred tempo for walking, which is about 120 bpm (MacDougall, 2005). Furthermore, walking with auditory stimuli is shown to be most synchronous at 120 bpm (Styns et al., 2007). As the rating of groove is shown to be related to the degree of sensorimotor synchronization (Janata et al., 2012), this suggests that our biomechanical characteristics are related to the rating of groove. These results indicate that perception of rhythm is an embodied perception.

2.4.4 Optimal tempo for groove and the complexity of rhythm

Although the optimal tempo for groove was shown to have a range of 107-126 bpm in the current study, the Monte Carlo simulation did not show a significant difference in the estimated optimal tempo between rhythmic patterns.

The reason behind this could be that, although the rhythmic pattern is shown to affect the rating of groove (Sioros et al., 2014; Witek et al., 2014), the effect of rhythm pattern was relatively small compared to the effect of tempo. In addition, the reason may be due to the inability of six tempo conditions to provide a precise regression model, which could have led to a large variance in each coefficient and thus a large variance in the estimated optimal tempo in the Monte Carlo simulation. Acquiring a more precise model by conducting another experiment with an additional variation of tempo might lead to a more complete conclusion. This needs to be investigated in a future study.

Furthermore, the variation of the rhythmic complexity could have affected the results. In the current study, the complexity of the rhythm was manipulated by shifting the position of each note in the musical score, while regulating the number of notes for each instrument. Therefore, there was a limitation in creating a rhythm pattern with high rhythmic complexity. In fact, the degree of syncopation can vary from 0 to 81 (Witek et al., 2014), while the highest degree of syncopation applied in the current study was 15. Therefore, applying a rhythm pattern with higher complexity might provide a different result.

2.4.5 Neurophysiological background

It has been revealed that groove not only induces subjective body movement, but also changes one’s neurophysiological state. Stupacher et al. (2013) revealed that listening to music with high groove ratings leads to increased activation in the primary motor cortex of musicians. Furthermore, it is well known that listening to rhythms activates areas of the brain related to movement, such as basal ganglia, supplementary motor area, premotor cortex, and cerebellum (Bengtsson et al., 2009; Chen et al., 2008b; Grahn and Brett, 2007; Grahn and Rowe, 2013; Kornysheva et al., 2010). In addition, it is reported that this activation is dependent on the tempo of the stimulus. For instance, activation in the basal ganglia is maximized when listening to rhythmic stimuli with IOI of 500-700 ms, or 87-120 bpm (Chen et al., 2006). These results suggest that groove, and those musical features related to groove, enhance activation in brain areas related to movement. This likely makes it easier to initiate movement, leading to an increase in spontaneous body movements.

2.4.6 Limitations

There are some limitations to the current experiment. Firstly, the detailed optimal tempo for groove is still unknown, because the smallest difference in tempo between the stimuli applied in the current study was 15 bpm. Providing stimuli with more precisely subdivided tempo and conducting an experiment within the range of 107 to 126 bpm, which was estimated to be the optimal tempo for groove in the current study, may lead to more revealing details concerning the optimal tempo for groove.

Secondly, although the current study concluded that there is an optimal tempo for groove, heart rate may affect these findings. It was shown in a previous study that preferred tempo is affected by heart rate (Iwanaga, 1995). This indicates that the tempo at which we feel comfortable changes depending on one’s heart rate, suggesting that the groove rating may also be affected by heart rate. If this is true, it is possible that there are lower and upper limits to the optimal tempo for groove, such as there are optimal limits in the heart rate. Therefore, there may be a trapezoidal relationship between groove rating and tempo rather than an inverted U-shaped relationship. This possibility could be investigated through an experiment as described below. Firstly, in order to investigate whether heart rate affects groove rating, participants rate groove of stimuli as was done in the current experiment and record their heart rate at the same time. An identical experimental procedure is repeated for several days, and the relationship between the estimated optimal tempo for groove and heart rate is investigated. If there is a positive correlation between the optimal tempo and heart rate, this would suggest that the optimal tempo for groove increases as heart rate increases, indicating that optimal tempo is affected by heart rate. Another possibility is that, if a logistic regression model fits better than a linear regression model, this would suggest that the optimal tempo is affected by heart rate only within a certain range, indicating that there is a trapezoidal relationship between groove rating and tempo. This needs to be investigated in future studies.

2.5 Conclusion

The study revealed that there is an optimal tempo for groove, which is approximately 107-126 bpm. However, there was no significant difference in the estimated optimal tempo between rhythmic patterns.

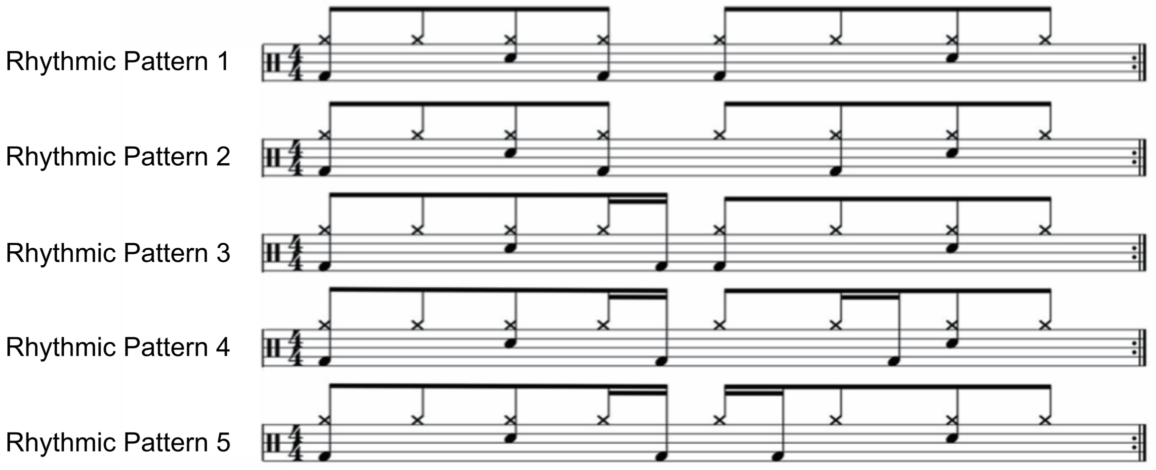
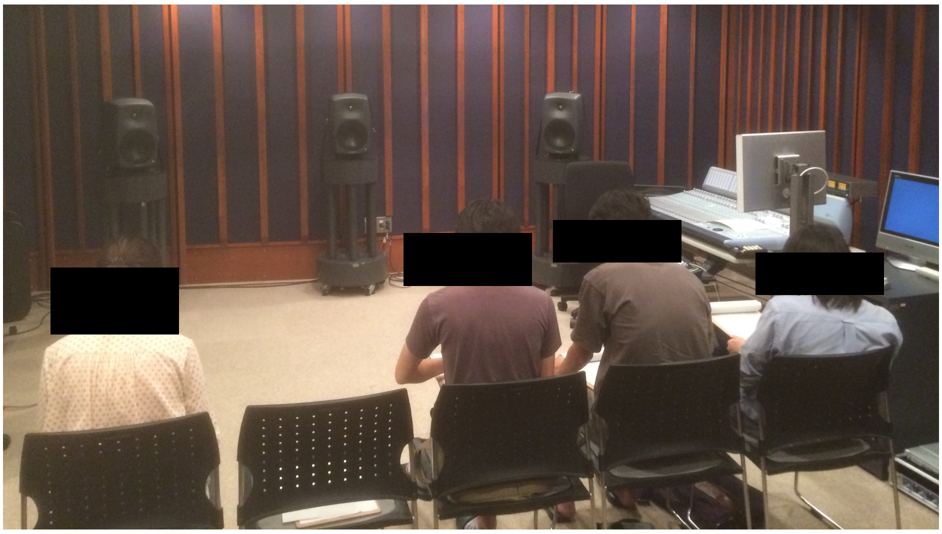



Figure 2-1. Five rhythmic patterns used as stimuli in the experiment. Notes on upper lines indicate hi-hat sounds, those on middle lines indicate snare drum sounds, and those of lower lines indicate bass drum sounds.



[redacted] [redacted] [redacted] [redacted]

Figure 2-2. The experiment was conducted in a sound proof room at Tokyo University of the Arts, Senju campus. Participants were seated in a chair and rated each stimulus presented via a loud speaker.

Table 2-1 Rating items used in the experiment (originally written in Japanese)

Performance with high groove
Performance with pulsing
Good “*nori*”
I think the tempo is fast
I feel excited
I want to move my body
I want to move my body back-and-forth
I want to move my body side-to-side
I feel pleasure
I feel like dancing
I feel like my body resonates with the rhythm

Table 2-2 Results of linear and quadratic regression analyses for each rhythmic pattern

Rhythmic pattern	Type of regression	B^2 (× 10^{-4}) [(SE) (× 10^{-5})]	B (× 10^{-3}) [(SE (× 10^{-3})]	Constant	Adjusted R^2	Estimated optimal tempo
Rhythmic pattern 1	Linear		−1.73	4.10**	−0.00	
			(1.99)			
	Quadratic	−1.31**	32.33**	2.20**	0.03	123.1
		(4.55)	(11.97)			
Rhythmic pattern 2	Linear		−1.11	4.42**	−0.00	
			(1.87)			
	Quadratic	−1.72**	43.4**	1.94**	0.07	126.4
		(4.20)	(11.03)			
Rhythmic pattern 3	Linear		−7.21**	5.11**	0.06	
			(1.96)			
	Quadratic	−2.30**	52.55**	1.78**	0.17	114.0
		(4.29)	(11.28)			
Rhythmic pattern 4	Linear		−8.89**	5.71**	0.10	
			(1.79)			
	Quadratic	−2.33**	51.62**	2.33**	0.23	110.6
		(3,85)	(10.11)			
Rhythmic pattern 5	Linear		−10.12**	5.55**	0.11	
			(1.94)			
	Quadratic	−2.22**	47.5**	2.34**	0.21	106.9
		(4.27)	(11.23)			

** $p < 0.01$, * $p < 0.05$

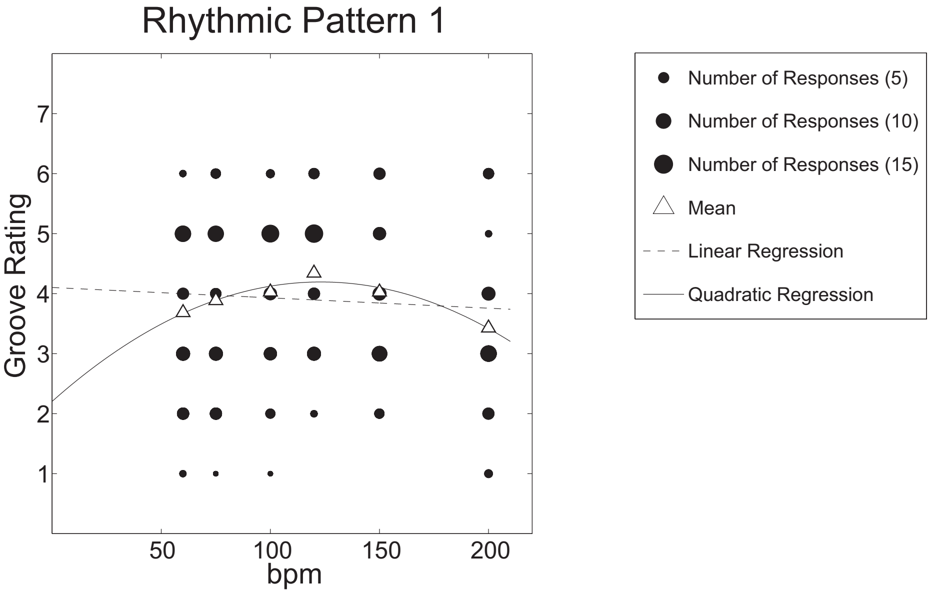


Figure 2-3A. Linear and quadratic regressions of Rhythmic Pattern 1.

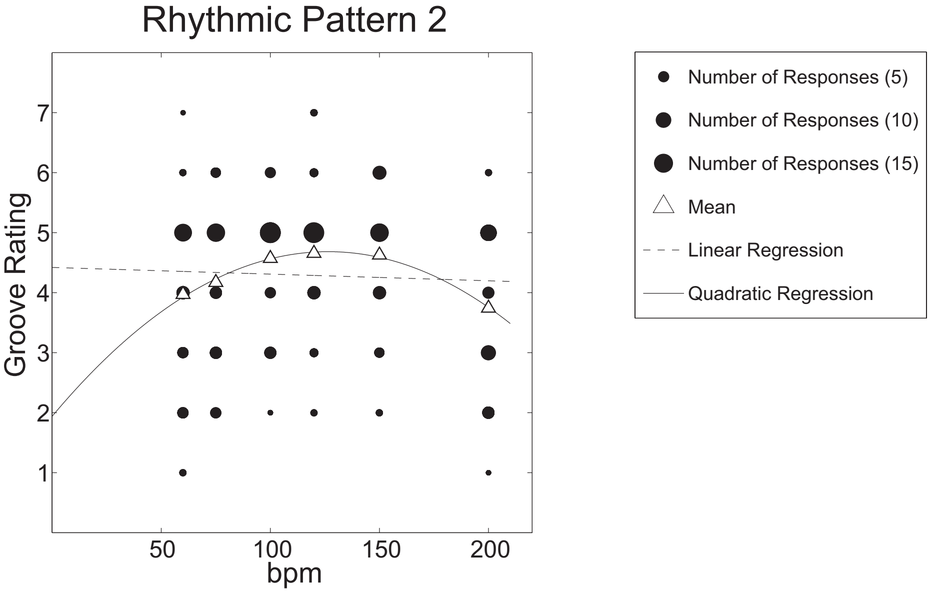


Figure 2-3B. Linear and quadratic regressions of Rhythmic Pattern 2.

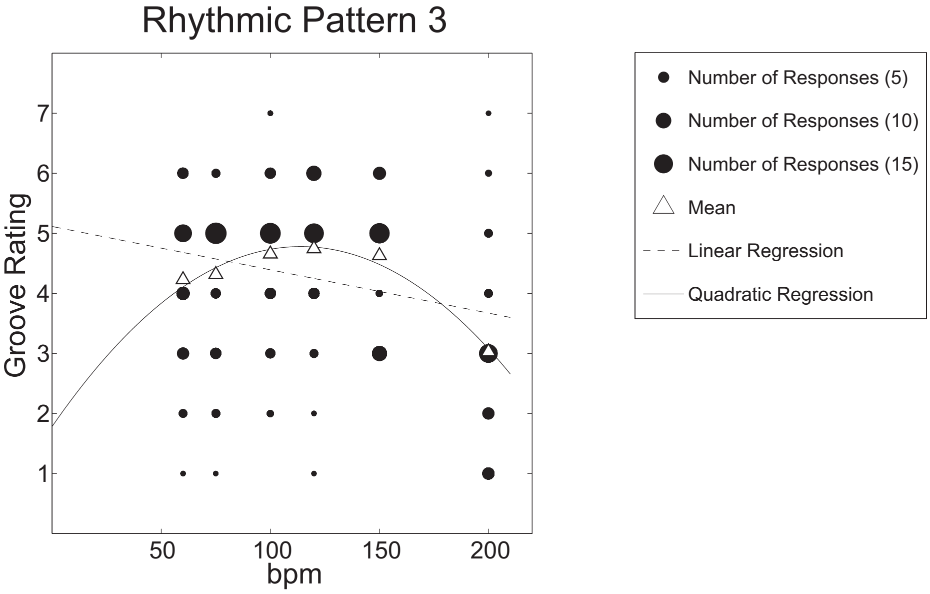


Figure 2-3C. Linear and quadratic regressions of Rhythmic Pattern 3.

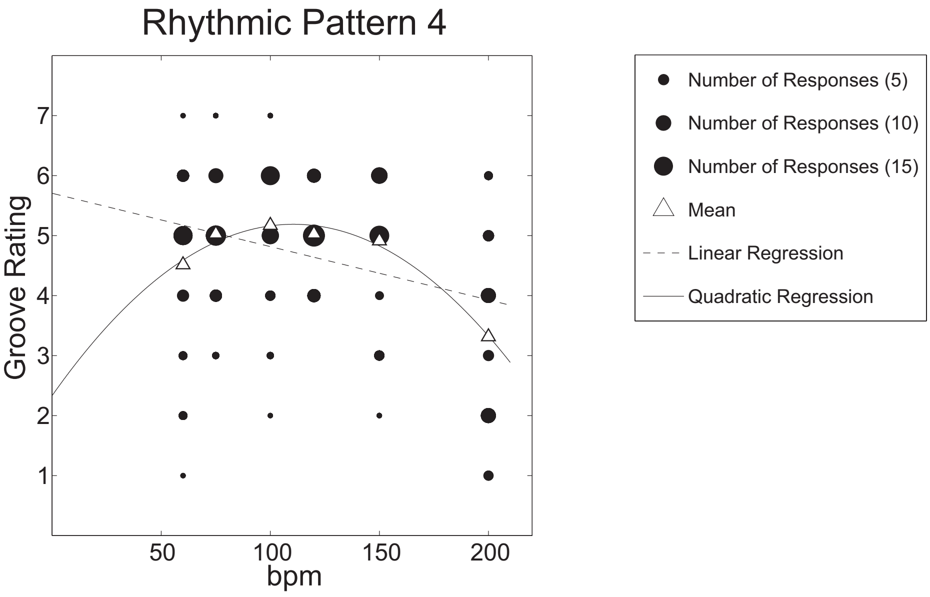


Figure 2-3D. Linear and quadratic regressions of Rhythmic Pattern 4.

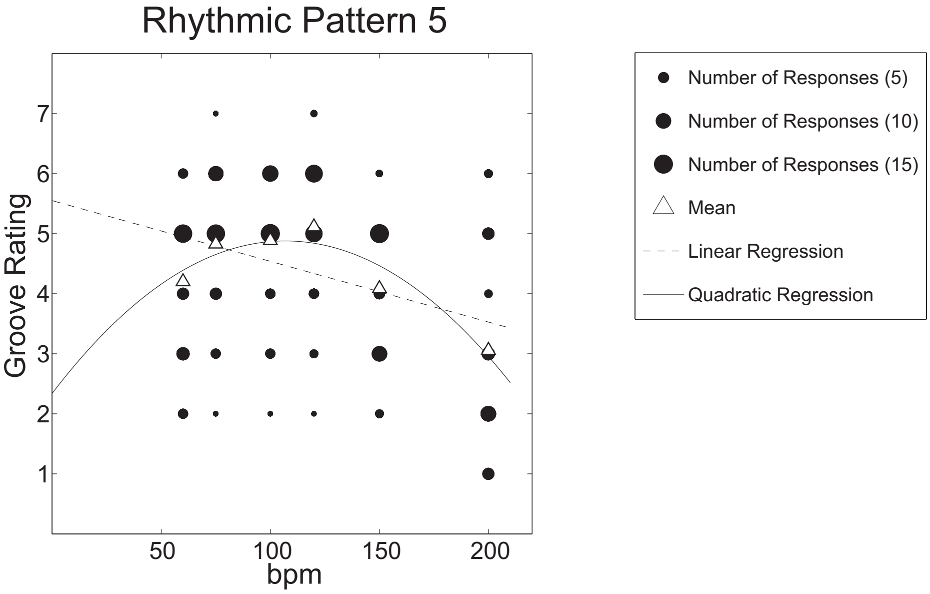


Figure 2-3E. Linear and quadratic regressions of Rhythmic Pattern 5.

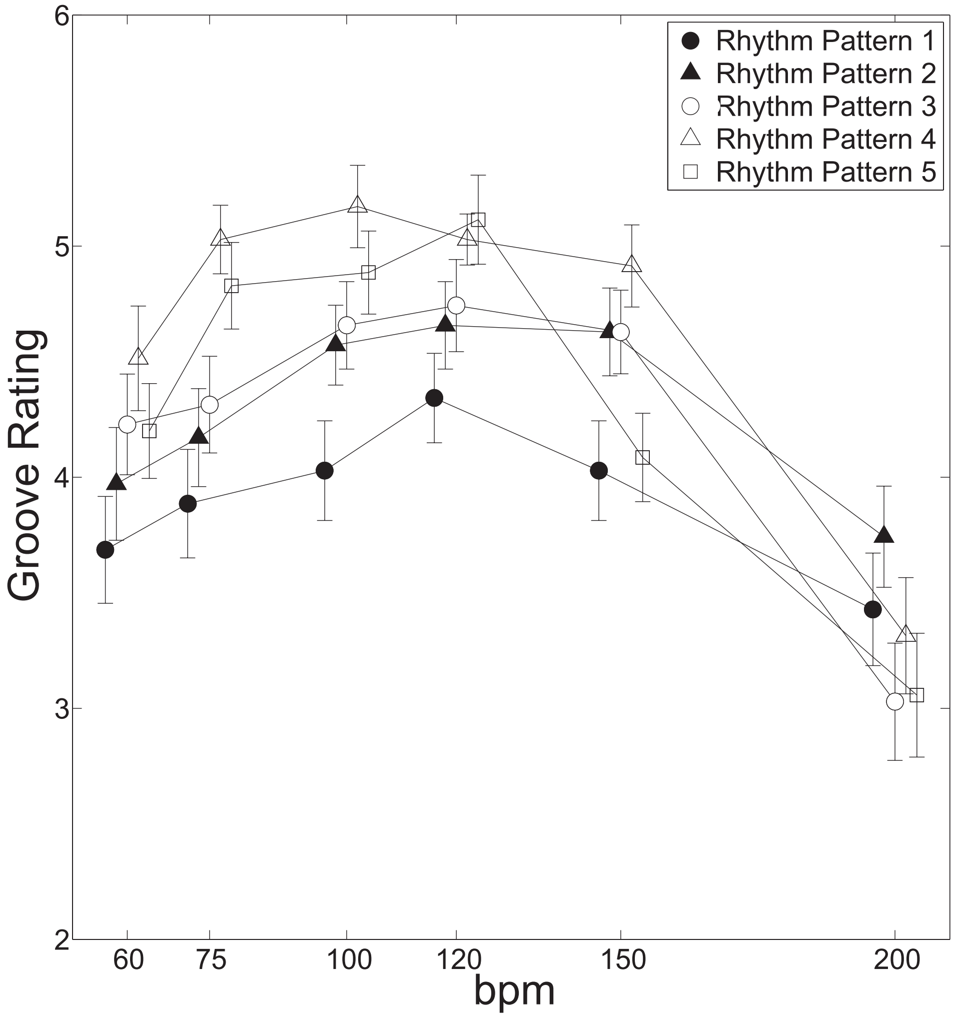


Figure 2-4. Mean groove rating for each stimulus. Error bars indicate standard errors.

2.6 Supplementary information

2.6.1 Correlations between the rating of groove and other items

In addition to investigating the relationship between groove and tempo, the relationship between groove and other items related to body movement and rhythm were also examined. Pearson’s correlation coefficient between rating for the item “Performance with high groove” (or simply groove) and other items were calculated. The first question was to confirm whether groove is regarded as an aspect of music that makes people want to move. The result showed a significant positive correlation between the items “Performance with high groove” and “I want to move my body” ($r = .81$, $p < .01$), indicating that groove is recognized as an aspect of music that induces body movement. The rating item that obtained the highest correlation coefficient with the rating of groove was “I feel like my body resonates with the rhythm” ($r = .91$, $p < .01$). This probably indicates that groove not only induces body movement, but also contributes to making this movement become more synchronized with the music.

Supplementary Table 2-1 Correlations between the rating of groove and other items

	Groove
Performance with high groove	–
I feel like my body resonates with the rhythm	0.91**
I feel pleasure	0.87**
I want to move my body side-to-side	0.86**
I want to move my body back-and-forth	0.82**
I want to move my body	0.81**
I feel excited	0.64**
Performance with pulsing	0.61**
I feel like dancing	0.59**
Good "*nori*"	0.58**
Fast tempo	−0.37*

** $p < .01$, * $p < .05$

Chapter 3:

Groove of rhythmic patterns on a snare drum with random timing fluctuation

3.1 Introduction

In Chapter 2, I focused on tempo, which has been given much attention by researchers. In Chapter 3, I will focus on expressive microtiming, which is also regarded as an important factor for groove.

3.1.1 Participatory discrepancies, or expressive microtiming

In musical performances, a variety of techniques are applied in order to enrich musical expressions. For instance, musicians often fluctuate the tempo or change the intensity of tones. Some of these expressions, such as accelerando, are written in the musical score, but musicians also give full attention to expressions that are not present in the written score. One example is participatory discrepancy (PD), or expressive microtiming (hereafter referred to as microtiming), which is a slight rhythmic deviation.

According to Butterfield (2006), PD is a "form of rhythmic displacement different from offbeat rhythms, syncopations, or anticipations. They are slight variations in timing, usually on the order of less than about 50 milliseconds (about 1/20th of a second), that purportedly generate some qualitative feeling of either rhythmic drive ("push") on the one hand, or relaxation ("layback") on the other." In fact, the existence of microtiming in actual performances has been confirmed in several studies (Alen, 1995; Davies et al., 2013; Prögler, 1995). By analyzing the performance of prominent jazz pianists Thelonious Monk and Ahmad Jamal, Iyer (2002) explains how microtiming is effectively applied to enrich their musical expressions.

3.1.2 Relationship between groove and microtiming

Microtiming (i.e., PD) is regarded as one important musical feature that helps engender groove (Iyer, 2002; Keil, 1995; Keil and Feld, 1994; Madison et al., 2011; Naveda et al., 2011). As formerly stated, groove is defined as a feeling or an aspect of music that makes people want to move (Madison et al., 2011; Stupacher et al., 2013).

Musicians also share this notion. For example, Fred Hersch, who is one of the greatest jazz pianists of his time, states, “There’s a certain kind of time that’s metronomic, that’s correct, but doesn’t make you want to dance. It doesn’t make you want to move, and it doesn’t make you want to play” (Berliner, 1994), suggesting the importance of microtiming for making people want to move, or creating groove. The belief that microtiming is a crucial aspect of groove is called PD theory.

Thus far, I have focused on the ideas of researchers and practices of musicians, but there is another aspect to consider: how does microtiming affect listeners? Several studies have shown that microtiming is not only a theory subscribed to by scholars and musicians, but is an actual factor that affects listeners’ attitudes towards music, especially as expressed in movement. Kilchenmann and Senn (2015) conducted an experiment in which people danced with musical excerpts of funk and swing music with varying magnitudes of microtiming and revealed that participants’ head movements were more synchronized to music in the 60 % reduced condition (having microtiming) as compared to the completely quantized condition. Additionally, another study showed that tapping to a chord (i.e., two sounds in this experiment) with a deviation decreased the variability of tapping (i.e., increased the stability of synchronization) compared to tapping to a chord without a deviation (Hove et al., 2007). These results support the concept of PD theory, which indicates that microtiming is relevant to groove as groove has been shown to enhance the synchronization of body movements to music (Janata et al., 2012).

3.1.3 Studies investigating the effect of microtiming on groove

Several studies have conducted cognitive experiments in order to investigate directly whether microtiming is crucial for groove (Davies et al., 2013; Madison et al., 2011; Senn et al., 2016, 2018). However, contrary to these intuitive and theoretical notions, none of them have reported any positive effect of microtiming on groove. For instance, some have reported that microtiming and groove have no significant relationship (Madison et al., 2011; Senn et al., 2018), that microtiming actually has a detrimental effect on groove (Davies et al., 2013; Frühauf et al., 2013), or that microtiming is not necessary for groove (Senn et al., 2016). Additionally, when musicians were asked to maximize or minimize groove when playing melodies by piano, it was reported that the microtiming never changed (Sioros et al., 2014). These studies indicate that perfectly quantized rhythms create the strongest groove. This notion is called the exactitude hypothesis (Kilchenmann and Senn, 2015).

Why is there such a discrepancy between well-established theoretical notions and these empirical results? One reason could be that it is difficult to recognize the effect of microtiming consciously. As at least one behavioral study has reported that microtiming affects the degree of synchronization (Kilchenmann and Senn, 2015), the effect of microtiming may only be visible in behavior at the subconscious level. Another possibility could be that microtiming, as it was applied in previous studies as a constant value, did not reflect how microtiming functions during live instrumental performances. Needless to say, professional musicians also demonstrate variability in timing when they play instruments (Fujii et al., 2011). For example, professional drummers exhibit a variability of 10 ms in standard deviation at 120 bpm when playing the snare drum (Fujii et al., 2011). Despite these facts, none of these earlier studies applied variable microtiming instead of using a constant value except one study, which applied the uniform distribution instead of the Gaussian distribution. This may have led listeners to perceive each stimulus with microtiming as unnatural, obtaining low ratings for groove, and those stimuli without microtiming as natural, leading to high ratings of groove.

3.1.4 Aims

In the current study, a cognitive experiment was conducted in order to investigate the effect of microtiming with random fluctuation following the Gaussian distribution, which is more like an actual performance compared to microtiming without variability, or with variability following the uniform distribution.

3.2 Methods

3.2.1 Participants

Twenty amateur musicians (23.6 ± 2.42) participated in the experiment. All but one participant majored in music at Tokyo University of the Arts. None of them reported any hearing problems.

3.2.2 Stimuli

A drum pattern consisting of a hi-hat, snare drum, and bass drum was provided for the experiment (Figure 3-1). Six stimuli following different Gaussian distributions with the standard deviations of 0, 5, 10, 15, 20, and 25 ms were provided (Table 3-1). These magnitudes were set according to a previous study reporting that professional drummers showed a variability of 10 ms in standard deviation when hitting a snare drum (Fujii et al., 2011), and that the variance of non-musicians is typically at least twice that of musicians (Repp, 2005c). The mean was set to 3 ms for all stimuli according to the previous study, which revealed that the snare drum was played with a constant delay compared to the high-hat and bass drum (Fujii et al., 2011). The tempo was set at 120 bpm. All stimuli were created by Max/MSP (ver 6.1.8), and the degree of microtiming (i.e., rhythmic deviation) was randomly applied according to each Gaussian distribution.

3.2.3 Apparatus

A laptop computer (MacBook Air), headphones (Sony/MDR-CD900ST), and an audio interface (Focusrite/Scarlett2i2) were used in this experiment.

3.2.4 Procedure

The experiment was conducted in a quiet room at Tokyo University of the Arts, Senju campus (Figure 3-2). Participants sat in a chair in front of a laptop computer. A paired comparison was applied in the experiment. First, two stimuli were played for 16 seconds each, and participants were instructed to choose the stimulus with stronger groove. They were free to compare two stimuli, if needed. Participants completed this procedure for all possible pairs (${}_6C_2$ = 15 pairs). The order of presentation was randomized. In this experiment, groove was defined as “the sensation of wanting to move” according to previous studies (Madison et al., 2011). Participants completed the task using a program provided by Max/MSP, listening to the stimuli through headphones (Sony/MDR-CD900ST). The experiment lasted about 15 minutes.

3.3 Results

3.3.1 Normalized Thurstone scale

In order to compare the degree of groove between each stimulus, the normalized Thurstone scale was calculated. To calculate the Thurstone scale, first, the total rate of selection for each pair was obtained (Table 3-2). The mean selection rate for 0, 5, 10, 15, 20, and 25 ms conditions were 0.75, 0.79, 0.63, 0.34, 0.30, and 0.19, respectively. Next, the Thurstone scale was obtained by calculating the inverse function of the normalized Gaussian distribution (Thurstone, 1927; Tsukida and Gupta, 2011; Woods et al., 2010) (Table 3-3). The results showed that the Thurstone scale for 0, 5, 10, 15, 20, and 25 ms conditions were 0.75, 0.92, 0.42, −0.58, −0.58, and −0.93, respectively (Figure 3-3).

3.3.2 Binomial test

In order to investigate if there is a significant difference in the selection rate between each stimulus, binomial tests were conducted. As each condition was not conducted independently, the level of significance was set to 0.33 % (i.e., 5 % divided by 15 conditions) applying the Bonferroni correction. The result showed that there was a significant difference in the selection rate in 8 pairs: 0 ms × 15 ms, 0 ms × 20 ms, 0 ms × 25 ms, 5 ms × 15 ms, 5 ms × 20 ms, 5 ms × 25 ms, 10 ms × 15 ms, and 10 ms × 25 ms conditions (*p*s < .0033).

3.4 Discussion

3.4.1 Summary of results

By applying paired comparisons, the effect of microtiming with random fluctuations following Gaussian distributions with various standard deviations on the rating of groove was investigated. The result of the Thurstone scale showed that the 5 ms condition obtained the highest value, followed by 0, 10, 15, 20, and 25 ms conditions. Then, the statistical significance of these results was investigated using binomial tests that showed that there was no significant difference in the selection rate between the 0 ms condition and 5 ms condition; however, there was a significant difference between the 0 ms × 15 ms, 0 ms × 20 ms, 0 ms × 25 ms, 5 ms × 15 ms, 5 ms × 20 ms, 5 ms × 25 ms, 10 ms × 15 ms, and 10 ms × 25 m conditions.

3.4.2 Is microtiming effective?

Several musicological studies (Iyer, 2002; Keil, 1995; Keil and Feld, 1994), behavioral studies (Kilchenmann and Senn, 2015), and the practice of musicians (Berliner, 1994; Iyer, 2002) have suggested the importance of microtiming for creating groove. However, contrary to these ideas, empirical studies have shown no positive effect of microtiming on creating groove (Davies et al., 2013; Madison et al., 2011; Senn et al., 2016, 2018). In the current study, I applied stimuli with random fluctuations, which are closer to timing deviations that arise during live instrumental performances, instead of using a constant value or that following the uniform distribution for microtiming like previous studies. The result of the Thurstone scale showed that the 5 ms condition had the highest selection rate on average. However, the result of the binomial test showed no significant difference in selection rate between these two conditions. This result suggests that microtiming does not necessarily produce stronger groove when compared to completely quantized stimuli without microtiming.

3.4.3 Acceptable range of microtiming

When focusing on distribution of the Thurstone scale, the stated result indicates that stimuli can be divided into two groups: (1) including the conditions of 0, 5, and 10 ms, and (2) including the conditions of 15, 20, and 25 ms. This is possible due to the relatively long distance observed between the 10 ms condition and 20 ms condition (Figure 3-3).

In other words, it is not as simple as the rating of groove increasing with a decrease in the magnitude of microtiming. If participants had chosen the stimulus with smaller microtiming in each comparison, the selection rates would have been 1.0, 0.8, 0.6, 0.4, 0.2, and 0 for the conditions of 0, 5, 10, 15, 20, and 25 ms, respectively. However, results demonstrated that the selection rates were 0,75, 0.79, 0.63, 0.34, 0.30, and 0.19, respectively (Table 3-3), and were not evenly spaced.

This result in grouping may reflect the acceptable range of microtiming. In other words, microtiming with the variability of 0-10 ms in standard deviation seems to be acceptable, while exceeding 15 ms in standard deviation is too large a variability to accept. Therefore, it is possible that there is an acceptable threshold for microtiming with variability between 10 and 15 ms in the standard deviation for creating groove.

The results of binomial tests also support this theory. Binomial tests revealed that the 0 ms condition and 5 ms condition obtained significantly higher selection rates than the 15, 20, and 25 ms conditions. In addition, the 10 ms condition had a significantly higher selection rate than the 15 and 25 ms conditions. This result also indicates that there are two groups: (1) one with smaller variability, including the conditions of 0, 5, and 10 ms, and (2) the other with a larger variability, including the conditions of 15, 20, and 25 ms, in consideration of results of the Thurstone scale and binomial tests.

This result indicates that microtiming is not necessary for creating groove and is not necessarily detrimental to creating groove. In other words, the results support neither PD theory nor the exactitude hypothesis but are in line with the results of Senn et al. (2016).

3.4.4 Limitations

Some limitations need to be mentioned. First, it is possible that the current study could not reflect the property of microtiming sufficiently. In the current study, microtiming with random fluctuation following Gaussian distributions was applied in order to imitate microtiming that accrues during actual instrumental playing. However, microtiming in live performances may follow not only a Gaussian distribution, but may also follow an order in time series, such as 1/*f* fluctuation. In fact, 1/*f* fluctuations are observed in various human rhythmic movements, such as walking (Hausdorff et al., 1995), running (Jordan et al., 2006; Nakayama et al., 2010), and finger tapping (Chen et al., 2002; Yamada, 1995). There have been studies that developed humanizing algorithms to apply pink noise to rhythmic fluctuation (Hennig, 2014; Hennig et al., 2011). In addition, they revealed that fluctuation with pink noise obtained higher ratings on preference compared to fluctuation with white noise (Hennig et al., 2011). Though this study did not ask participants to rate the degree of groove, the rating of groove may differ between pink noise and white noise. This needs to be investigated in future studies.

In addition, the relationship between groove and microtiming needs to be considered more in detail by applying finely subdivided measures of microtiming. The results of the current study suggest that there is a threshold for acceptable microtiming for groove and it is somewhere between 10 and 15 ms. Applying finely subdivided microtiming at smaller than 5 ms, which was used in the current study, and conducting an experiment within the range of 10 to 15 ms may lead to reveal a threshold of acceptable microtiming for creating groove. For instance, creating stimuli with the standard deviations of 10, 11, 12, 13, 14, and 15 ms, and conducting an experiment similar to the current study would lead to revealing the threshold of microtiming for groove to an accuracy of 1 ms.

In addition, applying microtiming on the snare drum may have been insufficient for imitating actual playing, because microtiming arises in all instruments, including hi-hats and bass drums (Fujii et al., 2011). Thus, it may be crucial to apply microtiming to all instruments used in order to investigate the effect of microtiming on groove.

In order to solve these problems, it is necessary first to more precisely analyze the properties of microtiming that develop during live performances, or physically playing an instrument. I will study this in a future project.

3.5 Conclusion

The result of the Thurstone scale and binomial tests indicated that there are two groups, acceptable range and non-acceptable range, in the variability of microtiming. This result suggests the presence of an acceptable range for microtiming, which supports neither the PD theory nor the exactitude hypothesis.

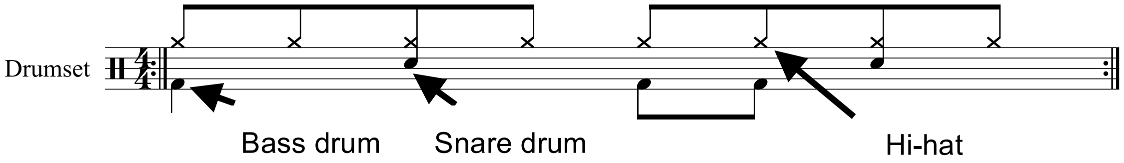


Figure 3-1. The rhythmic pattern of stimuli.

Table 3-1 Six stimuli with random timing fluctuations following six different Gaussian distributions

Stimulus	Mean (ms)	Standard deviation (ms)
Stimulus 1	3	0
Stimulus 2	3	5
Stimulus 3	3	10
Stimulus 4	3	15
Stimulus 5	3	20
Stimulus 6	3	25

Figure 3-2. The experiment was conducted in a quiet room at Tokyo University of the Arts, Senju campus.

Table 3-2 Selection rate for each pair

(The proportion of row items were rated to obtain higher groove in column items.)

	0 ms	5 ms	10 ms	15 ms	20 ms	25 ms
0 ms		0.45	0.70	0.90	0.85	0.85
5 ms	0.55		0.70	0.95	0.85	0.90
10 ms	0.30	0.30		0.85	0.80	0.90
15 ms	0.10	0.05	0.15		0.70	0.70
20 ms	0.15	0.15	0.20	0.30		0.70
25 ms	0.15	0.10	0.10	0.30	0.30	

Table 3-3 The Thurstone scale for each combination and mean of each condition

	0 ms	5 ms	10 ms	15 ms	20 ms	25 ms	Mean
0 ms		−0.13	0.52	1.28	1.04	1.04	0.75
5 ms	0.13		0.52	1.64	1.04	1.28	0.92
10 ms	−0.52	−0.52		1.04	0.84	1.28	0.42
15 ms	−0.28	−1.64	−1.04		0.52	0.52	−0.58
20 ms	−1.04	−1.04	−0.84	−0.52		0.52	−0.58
25 ms	−1.04	−1.28	−1.28	−0.52	−0.52		−0.93

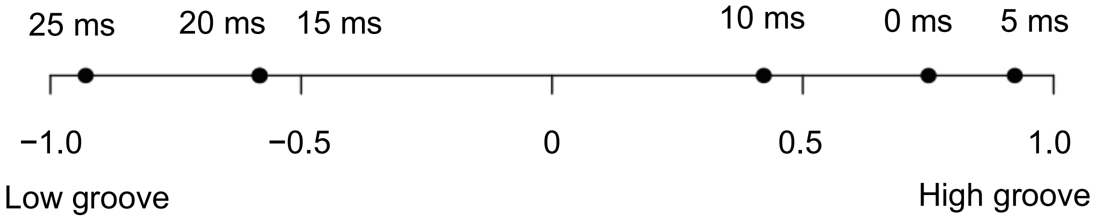


Figure 3-3. The normalized Thurstone scale for each condition.

Chapter 4:

Accent (groove) stabilizes 1:2 sensorimotor synchronization of rhythmic knee flexion-extension movement in upright stance

4.1 Introduction

So far, I focused on investigating musical features related to creating groove. Now, I will move on to the next question, “what are the functions of groove?” In this chapter, I will especially address the issue, whether groove contributes to enhancing body movement synchronization with music. Although a previous study revealed that music with high groove ratings enhance people’s synchronization to music (Janata et al., 2012), it is still unknown whether groove contributes to the entrainment because they only investigated the periodic similarity between music and the movement of tapping. In order to investigate the degree of entrainment, it is rather appropriate to focus on the phase between musical beat and the movement. As previous studies revealed that salient beat increases groove ratings (Madison et al., 2011), and that accent enhances beat salience (Parncutt, 1994), I investigated the effect of groove on sensorimotor synchronization (SMS) by comparing the stability of synchronization between a metronome with accented sounds (i.e., high beat salience) and a metronome without accented sounds (i.e., low beat salience).

The validity of applying a sound sequence with accented sounds as a sound sequence with groove, and a sound sequence without accented sounds as a sound sequence without groove is confirmed through a cognitive experiment, in which the sound sequence with accented sounds obtained higher groove ratings compared to the sound sequence without accented sounds (see 4.6 Supplementary information).

4.1.1 Widely shared musical features

The large variety of music styles around the world have multiple features in common (Brown and Jordania, 2013; Mehr et al., 2018; Savage et al., 2015); one example is that almost any music has a beat and a metrical structure. Many styles of music have co-evolved with dance, and in fact, there is increasing empirical evidence in the realm of psychology (Etani et al., 2018; Fujii et al., 2014; Janata et al., 2012; Levitin et al., 2018; Madison et al., 2011; Phillips-Silver and Trainor, 2005; Sioros et al., 2014; Zentner and Eerola, 2010) and neuroscience (Chen et al., 2006, 2008a; Grahn and Brett, 2007; Merchant et al., 2015; Patel and Iversen, 2014; Stupacher et al., 2013; Zatorre et al., 2007) revealing a strong connection between music and the body movements of humans. In addition, numerous studies have revealed the importance of metrical structure on beat perception and sensorimotor synchronization (SMS) theoretically (Large and Palmer, 2002; Large and Snyder, 2009; Merker, 2014; Vuust and Witek, 2014) and empirically (Fujioka et al., 2015; Madison, 2009; Phillips-Silver and Trainor, 2005, 2007), which indicates why metrical structure has evolved as a widespread musical element (Madison et al., 2017). In the current study, I aimed to investigate the effect of metrical structure on SMS stability, with a special focus on the effect of accent, which is a fundamental feature of metrical structure, on SMS with 1:2 subdivision.

4.1.2 Metrical structure and subdivision effect in sensorimotor synchronization

Meter is a temporal framework for perceiving rhythm (Vuust and Witek, 2014), and metrical structure is provided by a lower level of sounds with short intervals, and a higher level of sounds with longer intervals (Madison et al., 2011, 2017). For example, basic pulse (or beat) can be divided into sounds with shorter intervals, which is usually called subdivision, and several adjacent pulses can be integrated into a group of a longer interval, which typically makes a bar. When these sounds are distinguished by accents (provided by loudness, pitch, or timbre), we perceive meter (London, 2012). Furthermore, we also perceive subjective metrical structure from a sequence consisting of identical isochronous tones without any physical accent (Fujioka et al., 2015). Several studies have investigated the effect of metrical structure on SMS focusing on the subdivision using isochronous beats without physically accented tones.

Repp (2003) was the first to examine the effect of subdivision on the stability (i.e., temporal variability) of SMS. He provided 1:1, 1:2, 1:3, and 1:4 tapping conditions (tapping to every sound, every two sounds, every three sounds, and every four sounds, respectively), and compared the standard deviation of asynchrony, which is an indication of the stability of SMS. The results showed that when IOI (inter-onset interval) is above 200−250 ms, tapping with subdivisions (1:2, 1:3, and 1:4 tapping conditions) was more stable (temporally less variable) than tapping without any subdivision, which is 1:1 tapping, and that when the IOI is below 200−250 ms, tapping with subdivisions was less stable than 1:1 tapping. He termed the former effect as “subdivision benefit”, the latter effect as “subdivision cost”, and the IOI (200−250 ms), at which the effect of subdivision changes, as “cost-benefit transient point”. This transition point was in line with the hypothesis put forth by London (2002). Zendel et al (2011) conducted another 1:n tapping experiment in a wide range of tempi, to investigate whether the subdivision effect in 1:n tapping was caused by the IOI or ITI (inter-tap interval), which was not fully investigated in the previous study (Repp, 2003). They revealed that subdivision benefit was almost completely dependent on IOI, and that subdivision generally increases the performance of tapping when the IOI is above the cost-benefit transient point.

While the studies above applied metronome sequences with identical tones for any metrical level (subdivision level), Madison (2014) focused on the effect of both subdivision and physical accent. He provided stimuli whose tone had different loudness depending on the metrical level (1:1, 1:2, 1:4, and 1:8), and investigated the effect of subdivision at a wide range of tempi. He revealed that the variability of tapping decreases as the metrical level of a subdivision increases (i.e., IOI becomes shorter), and that this effect is salient as the ITI becomes longer. Importantly, he revealed that the subdivision cost reported by previous studies was absent, indicating that a sound sequence that is structured by physical accent prevents subdivision cost at fast tempi.

Although previous studies have shown the benefit of subdivision in SMS, none of them have compared the stability of SMS between sound sequences with physically accented sound and without physically accented sound within the same level of subdivision. In music, taking drum pattern as an example, the pulse is usually played by the bass drum, while the subdivision is added by another instrument such as a hi-hat. Thus, as in this example, the sound of pulse and subdivision is usually provided by different tones (loudness, pitch, or timbre) in music, which provides a clearer sense of rhythmic hierarchy. In fact, when dancing to music, people display various movements and characteristics of synchronization to music depending on the hierarchical level of the rhythm, such as the pulse, meter, and subdivision (Burger et al., 2013, 2014). Therefore, the stability of SMS to sound sequences with subdivision such as in a 1:2 SMS task may differ depending on whether the sequence has an accent or not. Previous studies have shown that the structure of sound sequences provided by accented sound (such as loudness) affects the maximal frequency at which participants can synchronize to (Repp, 2005b), and that off-beat tapping (tapping between the sounds) to a sound sequence with physically accented sound is more stable than tapping to a sound sequence without accented sound (Keller and Repp, 2005). These studies indicate that within the same subdivision level, for instance, 1:2 SMS with accented sound (e.g., synchronizing to a sound sequence consisting of loud sound and soft sound that appears alternately) would be more stable than 1:2 SMS without accented sound. Because previous studies focused on investigating the temporal variability, I aimed to assess the spatiotemporal characteristics of rhythmic coordination as a dynamical system. To do so, I investigated the behavior across a wide range of tempi, including the tempo at which people typically lose their stability, whereas in the previous studies (Keller and Repp, 2005; Repp, 2005b), the maximum tempo was restricted to the tempo at which participants can continue tapping with a metronome.

4.1.3 Intrinsically stable pattern in SMS

1:2 SMS with accented sound has two possible combinations of sound and movement: synchronization with accented sound and synchronization with non-accented sound. The stability of synchronization might also differ between these two conditions. Previous studies have reported that humans prefer an intrinsically stable SMS pattern (e.g., Kelso et al., 1990). This kind of stability is called a global stability (Fink et al., 2000). From now on, I would like to distinguish two kinds of stability: (1) the stability in terms of temporal variability will be described as “stability”, and (2) the stability in terms of resistant to phase transition or phase wandering will be described as “global stability.” Intrinsically stable patterns are generally observed in SMS tasks that apply a dynamical systems approach, in which people coordinate their rhythmic movement with external stimuli such as metronome beats, whose tempo gradually increases. In this paradigm, it is possible to investigate a globally stable coordination pattern of SMS as the stable pattern emerges (i.e., phase transition (transition from one pattern to another pattern) from a globally unstable coordination pattern to a globally stable coordination pattern) as the tempo increases. For instance, when coordinating the extension phase of rhythmic finger movement with a metronome, either phase transition (flexion phase is entrained to the beat) or phase wandering (loss of coordination) occurs as the tempo of the metronome increases (Carson, 1996; Kelso et al., 2001; Miura et al., 2016). These results indicate that flexion(down)-on-the-beat coordination is more globally stable than extension(up)-on-the-beat coordination when coordinating with a metronome. The enhanced global stability of flexion(down)-on-the-beat coordination compared to extension(up)-on-the-beat coordination is also observed in rhythmic knee flexion-extension movement in upright stance (Miura et al., 2011, 2013, 2018), which is typically seen in street dance. This observation is in line with the fact that people typically coordinate flexion (down) movement with the beat when dancing to music, suggesting that people’s basic dancing movement to music is the result of the organization of an intrinsically globally stable SMS pattern. Furthermore, although not physically differentiated, synchronizing to a subjectively accented sound is more stable than synchronizing to a non-accented sound (Repp, 2005a). Considering that flexion-on-the-beat is the intrinsically globally stable pattern, and that synchronizing to subjectively accented sound is stable together, flexing on physically accented sound would be more globally stable than flexing on non-accented sound in 1:2 SMS tasks. In addition, if flexing on accented sound (flexion-on-the-accent) is more globally stable, increasing the tempo while flexing on non-accented sound (extension-on-the-accent) may lead to a phase transition to the flexion-on-the-accent pattern. In addition to investigating whether accented sound would globally stabilize 1:2 SMS, I also aimed to investigate whether a phase transition from extension-on-the-accent to flexion-on-the-accent would occur, which will enable us to quantify the global stability (Fink et al., 2000).

4.1.4 Stability and movement amplitude

Several studies have investigated the relationship between the stability of coordination and the movement amplitude in a bimanual coordination task (Jirsa et al., 2000; Kudo et al., 2006; Schwartz et al., 1995). In these studies, the authors compared two conditions of coordinating either maximal flexion or maximal extension of rhythmic bimanual movement with a metronome (single metronome condition), and coordinating both maximal flexion and maximal extension with a metronome (double metronome condition), revealing that variability of the relative phase between two hands is smaller in the double metronome condition than in the single metronome condition. As such, rhythmic auditory beats have been reported to stabilize oscillatory human movements, which is known as an anchoring effect (Byblow et al., 1994). In addition to the stability, they revealed that in the double metronome condition, the amplitude was larger than that in the single metronome condition, suggesting that increased movement amplitude is related to a stabilized coordination (Jirsa et al., 2000; Kudo et al., 2006). Therefore, higher SMS stability that may be more associated with metrical structure with accented sounds than with metrical structure without accented sounds can lead to larger movement amplitude. Another possibility is that loud sound itself elicits larger movement amplitude (Van Dyck et al., 2013). In order to investigate these possibilities, two metronome conditions were provided in the current study: one repeating loud sound and soft sound alternately, and one repeating only loud sound. If the metrical structure with accented sounds is associated with larger movement amplitude, larger amplitude should be observed in the former condition. If loud sound is associated with larger movement amplitude, larger movement amplitude should be observed in the latter condition.

4.1.5 Aims and hypotheses

In this study, I conducted a 1:2 SMS (synchronizing flex movement, once, every two sounds) experiment in which participants synchronized their rhythmic knee flexion-extension movement in upright stance to a metronome with and without accented sound, and investigated three hypotheses: (1) synchronizing to a metronome with accented sound would be more stable than synchronizing to a metronome without accented sound, (2) flexing on accented sound (flexion-on-the-accent) would be more globally stable than flexing on non-accented sound (extension-on-the-accent) and phase transition from flexion-on-the-accent to extension-on-the-accent would occur at fast tempi, and (3) the amplitude of the knee flexion-extension movement would increase in stable conditions. This study is significant because it is the first, to investigate the contribution of accented sounds to SMS within the same level of subdivision and the global stability of SMS by applying a dynamical systems approach; previous studies have only focused on the stability in terms of the temporal variability.

I applied the rhythmic knee flexion-extension movement in upright stance as a task because I aimed to investigate the effect of accent structure on the SMS of this movement directly. Although various studies have revealed the effect of accent structure on the SMS of finger tapping, it is possible that the results would differ between the SMS of finger tapping and rhythmic knee flexion-extension movement in upright stance. For instance, in rhythmic knee flexion-extension movement in upright stance, it is necessary for the individual to maintain balance and coordinate ankle joint and the hip joint movements in addition to the knee joint movements. Furthermore, the vestibular system, which is recruited in the rhythmic knee flexion-extension movement in upright stance, has been shown to affect rhythm perception (Phillips-Silver and Trainor, 2005, 2007). In fact, the frequencies of phase transition (from up-on-the-beat to down-on-the-beat) in the SMS of finger tapping and that of rhythmic knee flexion-extension movement in upright stance are not the same (Miura et al., 2013, 2016).

The validity of applying this rhythmic knee flexion-extension movement in upright stance has been shown in previous studies, and this is a basic movement for street dance. Particularly, two basic coordination modes exist for the rhythmic knee flexion-extension movement in upright stance: coordinating flexion movement with the beat and coordinating extension movement with the beat. Miura et al. (2013) succeeded in revealing the difference in skills between novice and skilled dancers applying this rhythmic knee flexion-extension movement in upright stance. Furthermore, the same rhythmic knee flexion-extension movement in upright stance has also been applied in other studies, revealing that visual information affects the frequency of phase transition of SMS (Miyata et al., 2017, 2018).

I applied a dynamical systems approach in the current study because the SMS of rhythmic knee flexion-extension movement in upright stance has been investigated by applying a dynamical systems approach (e.g., Miura et al., 2011, 2013, Miyata et al., 2017, 2018; Miyata and Kudo, 2014). In a dynamical systems approach, stability of synchronization is often investigated by comparing the variance of phase angle at the beat onset (Miura et al., 2011). Additionally, in a dynamical systems approach, a globally stable coordination pattern is investigated by observing a phase transition from one pattern to another pattern, which can be observed by gradually increasing the tempo of the metronome while synchronizing rhythmic movement with the metronome beats. For instance, it has been reported that a phase transition from extension-on-the-beat (coordinating extension movement with the beat) to flexion-on-the-beat (coordinating flexion movement with the beat) occurs when starting the task with extension-on-the-beat and gradually increasing the tempo (e.g., Miura et al., 2013). Because one purpose of the current study was to investigate whether there would be a globally stable coordination pattern (flexion-on-the-accent vs. extension-on-the-accent), I decided to apply a dynamical systems approach in the current study.

4.2 Methods

4.2.1 Ethics statement

The study was approved by the Ethics Committee of the Graduate School of Arts and Sciences, the University of Tokyo.

4.2.2 Participants

Fourteen healthy adults (24.6 ± 2.6 years old) participated in the experiment. All participants received aural and written instructions and provided written informed consent before the experiment.

4.2.3 Procedure

Participants were instructed to synchronize their rhythmic down-up (knee flexing and extending) movement with a metronome (one sound with flexion phase, and one sound with extension phase) while standing on the ground (Figure 4-1). During the task, they were instructed to cross their arms in front of their body, and to look at the black curtain in front of them in order to avoid any visual effect. The black curtain was placed 70 cm in front of the participants, and a loudspeaker (Foster Electric Company Ltd., Japan) was placed 50 cm behind the participants, and 90 cm above the ground.

The experiment lasted approximately one hour. To avoid the effect of fatigue, sufficient rest was provided between each trial.

4.2.4 Stimuli

Three types of metronome stimuli were used in the experiment: metronome repeating loud sound and soft sound alternately, metronome repeating soft sound and loud sound alternately, and metronome repeating loud sound. All stimuli consisted of 440 Hz pure tone for a duration of 25 ms (created using MATLAB [Mathworks, USA]). The ratio of the sound amplitude between soft and loud sounds was set to 1:9. Each stimulus consisted of 220 tones that accelerated from 2.0 to 8.0 Hz logarithmically. The BPM was increased at a rate set to +0.64 percent to investigate the stability of SMS because a previous study reported that people can synchronize to a metronome with a change in BPM rate of ±0.077 to ±0.67 percent (Madison and Merker, 2005). I used a metronome with a gradual tempo increase because previous studies have investigated phase transitions in bimanual finger coordination tasks and SMS tasks by applying tempo as a control parameter (i.e., observing the coordination behavior along with the tempo increase) in a dynamical systems approach (e.g., Carson et al., 2009; Kelso et al., 1990). Thus, using a metronome with a gradual tempo increase enables us to determine the frequency at which phase transition occurs. For instance, Kelso (1984) revealed that in a bimanual finger coordination task, a phase transition from anti-phase coordination mode to in-phase coordination mode occurs as the tempo increases. As in this example, one can investigate the phase transition from one pattern to a more globally stable pattern by gradually increasing the tempo while completing tasks such as the bimanual finger coordination task and sensorimotor synchronization task. Because I predicted a phase transition from extension-on-the-accent to flexion-on-the-accent at fast tempi, I also applied a metronome with a gradual tempo increase to investigate the occurrence of phase transition as performed in previous studies.

4.2.5 Experimental condition

Six conditions combining three sound-movement conditions and two starting conditions were provided. The three sound-movement conditions were as follows: (1) combining the flexion phase with loud sound and the extension phase with soft sound (flexion-on-the-accent condition), (2) combining the flexion phase with soft sound and the extension phase with loud sound (extension-on-the-accent condition), and (3) combining both phases with loud sound (no-accent condition) (Figure 4-2). The two starting conditions were as follows: (1) starting with the flexion phase, and (2) starting with the extension phase. Although the aim of this study was to investigate the effect of the sound-movement conditions, the effect of the starting condition was also examined in the experiment. This is because I wanted to confirm that the sound-movement condition rather than the order of sound (i.e., whether accented sound or non-accented sound comes first) has affected the performance, if any difference in the stability is observed between the flexion-on-the-accent condition and extension-on-the-accent condition. All participants completed three sets of six conditions.

4.2.6 Apparatus and data collection

During the experiment, right knee angular displacement was recorded using a goniometer (Biometrics Ltd, UK) with a sampling rate of 1000 Hz. The goniometer was connected to a data acquisition device (National Instruments, USA), and was recorded using LabVIEW (National Instruments, USA). The metronome beat was presented via an iPhone 6S (Apple, USA) connected to the speaker and was also recorded using

LabVIEW.

4.2.7 Data analysis

Data analysis was conducted using Matlab (MathWorks, USA).

Stability and global stability of SMS

As an index of SMS stability, the proportion of stable and unstable states was calculated. The calculation procedure was as follows.

Firstly, the knee angular displacement was low-pass filtered (Butterworth filter, 10 Hz), and the angular velocity was obtained by differentiating the knee angular displacement. Both the angular displacement and the angular velocity were then normalized (Z-scored) between each beat onset. The phase angle defined as $\phi = tan^{-1} \frac{\omega}{\theta}$ at each beat onset was calculated (ω represents the angular velocity, and θ represents the angular displacement) (Figure 4-3AB).

In this study, to investigate the stability of the SMS and the occurrence of phase transition, I divided the state of SMS at each beat onset into three states: (1) stable state without transition, (2) stable state with transition, and (3) unstable state. The detailed process used for the categorization is described below. In this analysis, I applied the data of the phase angle of the flexion movement.

First, moving circular variance (n-1, n, n+1) of the phase angle was calculated as an index of the stability. Then, I removed the first two and the last data points of moving variance, and the first three and the last two data points of the phase angle, obtaining 105 data points in total for each trial. I calculated each moving variance using three data points because the stability in the SMS task is usually lost abruptly when phase transition occurs (Kelso et al., 1986).

Then, to divide each state into stable and unstable states, I defined the stable state as that whose circular variance is lower than or equal to 0.12, and the unstable state as that whose circular variance is greater than 0.12. The threshold of 0.12 was applied according to a previous study (Miura et al., 2011) which showed that the mean of the circular standard deviation + 2 × between-subject SD of phase angle in the flexion-on-the-beat condition at 100 bpm (non-dancer) was approximately 30 degrees, which is a circular variance of 0.12. I defined the *n*th state as that whose variance is lower than or equal to this threshold (0.12) as stable.

Next, I divided the stable state into a stable state without transition and a stable state with transition. Transition here means that the combination of sound and movement is reversed from the instructed combination. First, I calculated the mean phase angle of the first 20 beats of all participants, which was 225 degrees. Then, I defined the range of 225 ± 90 degrees (i.e., 135-315 degrees) as the flexion range, and the range of 0-135 or 225-360 degrees as the extension range (Figure 4-4). If the *n*th variance was lower than or equal to 0.12, and the *n*th phase angle was included in the flexion range (135-315 degrees), the *n*th state was defined as the stable state without transition. If the *n*th variance was greater than 0.12, and the *n*th phase angle was included in the extension range (0-135 or 225-360), the *n*th state was defined as the stable state with transition. In summary, I divided *n*th state into three states of (1) stable state without transition, (2) stable state with transition, and (3) unstable state according to the *n*th moving variance and the *n*th phase angle. This division process has also been described in the diagram (Figure 4-5).

Finally, I divided 105 states into 5 tempo ranges (21 states in each tempo range), and calculated the percentage of (1) stable state without transition, (2) stable state with transition, and (3) unstable state for each tempo range. Tempo range 1, 2, 3, 4, and 5 represents 2.1-2.7 Hz, 2.7-3.5 Hz, 3.5-4.6 Hz, 4.6-6.0 Hz, and 6.0-7.8 Hz, respectively. Circular statistics were used for calculating the mean and the variance of the phase angle (Batschelet, 1981).

Movement amplitude

As an index of movement kinematics, the amplitude of the knee flexion-extension movement was calculated. Firstly, I obtained the peaks of extension movement (the point of maximal knee extension), and the peaks of flexion movement (the point of maximal knee flexion). The amplitude was defined as the average of the absolute difference of the *n*th flexion peak and the *n*th extension peak at each tempo range.

4.2.8 Statistical analysis

Statistical analysis was conducted using SPSS Statistics 20 (IBM, USA).

Analysis of the SMS stability

The proportion of the stable state (sum of the proportion of the stable state without transition and stable state with transition) was compared between each condition by conducting three-way repeated measures ANOVA with the factors of sound-movement condition (flexion-on-the-accent, extension-on-the-accent, no-accent), starting condition (starting with flexion, starting with extension), and tempo condition (tempo ranges 1 to 5). Greenhouse-Geisser correction was applied for the violations of sphericity assumption. Multiple comparisons with Bonferroni correction were applied in the *post hoc* analyses; the significance level was set to $p < .0167$.

Analysis of the phase transition

The proportion of the stable state with transition was compared between the accent conditions (flexion-on-the-accent condition and extension-on-the-accent condition) by conducting three-way repeated measures ANOVA with the factors of sound-movement condition (flexion-on-the-accent, extension-on-the-accent), starting condition (starting with flexion, starting with extension), and tempo condition (tempo ranges 1 to 5). Greenhouse-Geisser correction was applied for the violations of sphericity assumption. Multiple comparisons with Bonferroni correction were applied in the *post hoc* analyses; the significance level was set to $p < .0167$.

Analysis of the movement amplitude

The amplitude was compared between each condition by conducting three-way repeated measures ANOVA with the factors of sound-movement condition (flexion-on-the-accent, extension-on-the-accent, no-accent), starting condition (starting with flexion, starting with extension), and tempo condition (tempo ranges 1 to 5). Greenhouse-Geisser correction was applied for the violations of sphericity assumption. Multiple comparisons with Bonferroni correction were applied in the *post hoc* analyses; the significance level was set to $p < .0167$.

4.3 Results

4.3.1 Stability of SMS

A typical example of phase plane trajectory and beat onsets for each sound-movement condition (2.1-7.8 Hz) is shown in Figure 4-6. Beat onsets that need to be synchronized with extension movements are described in white circles with red edge.

Proportion of the stable state

The results of the three-way repeated measures ANOVA indicated that the main effects of the sound-movement condition ($F_{(1.07,\ 13.88)} = 10.40$, $p = .006$, $\eta^2 = .444$) and the tempo condition ($F_{(1.42,\ 18.41)} = 42.41$, $p = .000$, $\eta^2 = .765$) were significant. The sound-movement condition × tempo condition interaction ($F_{(1.68,\ 21.87)} = 7.69$, $p = .004$, $\eta^2 = .372$) was also significant. The main effect of the starting condition ($F_{(1.00,\ 13.00)} = 1.70$, $p = .215$, $\eta^2 = .115$), tempo condition × starting condition interaction ($F_{(2.36,\ 30.69)}$

= 0.46, p = .670, η^2 = .034), sound-movement × starting condition interaction ($F_{(1.25, 16.25)}$ = 3.78, p = .062, η^2 = .225), and tempo condition × sound-movement condition × starting condition interaction ($F_{(4.03, 52.41)}$ = 1.43, p = .237, η^2 = .099) were not significant.

As the interaction of the sound-movement condition × tempo condition was significant, I conducted a *post hoc* analysis (Figure 4-7). The analysis revealed that the proportion of stable states was larger in the flexion-on-the-accent condition than in the no-accent condition in the tempo range 3 ($p < .0167$). In addition, the proportions of stable states were larger in the flexion-on-the-accent condition and extension-on-the-accent condition than in the no-accent condition in tempo range 4 and 5 (ps < .0167).

Proportion of the stable state with transition

Results of the three-way repeated measures ANOVA indicated that the main effects of the sound-movement condition ($F_{(1.00, 13.00)}$ = 13.76, p = .003, η^2 = .514), the tempo condition ($F_{(2.02, 26.26)}$ = 24.32, p = .000, η^2 = .652), and the starting condition ($F_{(1.00, 13.00)}$ = 11.27, p = .005, η^2 = .464) were significant. The sound-movement condition × tempo condition interaction ($F_{(1.79, 23.30)}$ = 15.12, p = .000, η^2 = .538) and the tempo condition × starting condition interaction ($F_{(2.21, 28.69)}$ = 3.97, p = .027, η^2 = .234) were also significant. The sound-movement condition × starting condition interaction ($F_{(1.00, 13.00)}$ = 3.91, p = .070, η^2 = .231) and the tempo condition × sound-movement condition × starting condition interaction ($F_{(2.33, 30.26)}$ = 1.31, p = .286, η^2 = .092) were not significant.

As the interaction of the sound-movement condition × tempo condition was significant, I conducted a *post hoc* analysis (Figure 4-8). The analysis revealed that the proportion of transitioned stable states were larger in the extension-on-the-accent condition than in the flexion-on-the-accent condition in tempo range 4 and 5 (ps

$< .0167$).

4.3.2 Movement amplitude

The results of the three-way repeated measures ANOVA indicated that the main effects of the sound-movement condition ($F_{(1.89, 24.58)} = 5.94$, $p = .009$, $\eta^2 = .314$) and the tempo condition ($F_{(1.26, 16.32)} = 61.64$, $p = .000$, $\eta^2 = .826$) were significant. The sound-movement condition × tempo condition interaction ($F_{(2.42, 31.46)} = 8.59$, $p = .001$, $\eta^2 = .398$) was also significant.

As the interaction of the sound-movement condition × tempo condition was significant, I conducted a *post hoc* analysis (Figure 4-9). The result revealed that the amplitude was significantly larger in the extension-on-the-accent condition than in the no-accent condition in tempo range 4 ($p < .0167$). In addition, the amplitudes were larger in the flexion-on-the-accent condition and extension-on-the-accent condition than in the no-accent condition in tempo range 5 ($p < .0167$).

4.4 Discussion

4.4.1 Summary of the results

In the current study, I conducted a 1:2 SMS experiment in which participants synchronized their rhythmic knee flexion-extension movement in upright stance with a metronome with accented sound and without accented sound, and investigated three hypotheses: (1) synchronizing to a metronome with accented sound would be more stable than synchronizing to a metronome without accented sound, (2) flexing on accented sound (flexion-on-the-accent) would be more globally stable than flexing on non-accented sound (extension-on-the-accent) and phase transition from flexion-on-the-accent to extension-on-the-accent would occur at fast tempi, and (3) the amplitude of the knee flexion-extension movement would increase in stable conditions.

The results of ANOVAs showed that the proportion of the stable state in the accent conditions (flexion-on-the-accent, and extension-on-the-accent) were larger than that of the no-accent condition in the tempo range 3 to 5, suggesting that 1:2 SMS with accented sound is more stable than 1:2 SMS without accented sound. In addition, the proportion of the stable state with transition was larger in the extension-on-the-accent condition, compared to the flexion-on-the-accent condition in the tempo range 4 and 5, which indicates that the flexion-on-the-accent condition is the preferable globally stable coordination pattern in 1:2 SMS with accented sound. Finally, the amplitude of the movement was larger in the accent conditions than the no-accent condition in the tempo range 4 and 5. Because higher stability was also observed in this tempo range, this result suggests that larger movement amplitude is associated with high stability in SMS.

4.4.2 Stability and global stability of SMS

It is known that sound affects the stability of movement. For instance, a previous study revealed that vocalization enhances the stability of SMS (Miyata and Kudo, 2014). In addition, the characteristics of sound, such as subdivision (Madison, 2014; Repp, 2003; Zendel et al., 2011) and accent (Keller and Repp, 2005; Repp, 2005b) were demonstrated to enhance the stability of SMS. In addition to these findings, the current study revealed that 1:2 SMS with physically accented sound is more stable than 1:2 SMS without physically accented sound in rhythmic knee flexion-extension movement in upright stance.

In the current experiment, a significant difference in the stability of SMS was observed between the accent conditions (flexion-on-the-accent and extension-on-the-accent) and the no-accent condition in the tempo range 3, 4, and 5, which is 3.5−7.8 Hz. The IOI of the tempo range 3, in which a significant difference in the stability was first observed, was 218−282 ms. Although it might not be appropriate to directly compare our study results with those of the previous study (Repp, 2003) because I did not apply the same task as that in the previous study, the IOI range in our study is close to that at which the subdivision benefit was lost (i.e., 200−250 ms). Thus, when accent is added in the 1:2 SMS condition, either the subdivision benefit remains, or the subdivision cost does not accrue even if the IOI is shorter than 200−250 ms.

Furthermore, the current study showed that 1:2 SMS with accented sound was almost equally as stable as 1:2 SMS without accented sound at the IOI above 200−250 ms (roughly at the tempo range 1 and 2), in which subdivision benefit has been reported in previous studies (Repp, 2003; Zendel et al., 2011). Therefore, the results of both Madison's (2014) study and our study suggest that subdivision with physically accented sound stabilizes SMS at a wide range of tempi.

There are two possible explanations as to why metrical structure with accented sounds stabilized 1:2 SMS. First, auditory stream segregation may have contributed to facilitate auditory perception, leading to stable coordination in the accent conditions. Auditory stream segregation is a phenomenon in which an auditory stream is perceived as separate streams (Bregman, 1990). For instance, when high- and low-pitched sounds are presented alternately at fast tempi, people perceive it as two different streams of high- and low-pitched sounds (Bizley and Cohen, 2013; Bregman and Campbell, 1971). This phenomenon is also observed when a sound is presented alternately with high and low intensity (van Noorden, 1975). Therefore, in the current experiment, participants likely perceived the metronome as two separate streams at fast tempi: one with loud sounds and the other with soft sounds. This enabled them to synchronize flexion (or extension) movement with a stream of either loud sound or soft sound, which may have made the synchronization easier, instead of coordinating both the flexion and extension phases with each sound.

Second, it is possible that the entraining characteristic of the metronome sound contributed to the result. It is known that the flexion phase and the movement that coincides with the direction of gravity tend to be entrained to the metronome sound in SMS of rhythmic knee flexion-extension movement in upright stance (Miura et al., 2011, 2013, 2015, 2018). In the no-accent condition, participants were required to coordinate the flexion and extension phases to metronome sounds of equal intensity. Therefore, as a metronome sound tends to entrain the flexion movement more than the extension movement, it is possibly difficult for participants to resist against this entrainment when coordinating the extension phase with the metronome sound, leading to destabilization of SMS in the no-accent condition.

In addition, as a phase transition from extension-on-the-accent to flexion-on-the-accent was observed, our results suggest that flexion-on-the-accent is a preferred globally stable pattern in 1:2 SMS with accented sound. More specifically, coordination of the flexion phase with loud (accented) sound was more globally stable than coordination of the extension phase with loud (accented) sound in the accent conditions, suggesting a global stability of the flexion-on-the-accent pattern. As stated above, the flexion movement tends to be entrained to the beat in SMS of rhythmic knee flexion-extension movement in upright stance (Miura et al., 2011, 2013, 2015, 2018). In addition, loud sound elicits stronger attention, and reduced cognitive demand leads to stronger synchronization (Zivotofsky et al., 2018). Therefore, synchronizing the flexion phase with the accented sound was more globally stable than synchronizing the extension phase with the accented sound, because the former coordination required less cognitive demand. Furthermore, as a previous study showed that tapping to subjectively accented sound is more stable than tapping to non-accented sounds (Repp, 2005b), coordinating flexion movement to both subjectively and physically accented sound may enhance the global stability of SMS.

4.4.3 The relationship between coordination stability and movement amplitude

The current study revealed that the SMS is more stable and the movement amplitude is larger in the accent condition than in the no-accent condition. As the loud-loud condition (no-accent condition) did not elicit a larger movement amplitude, the result indicates that it was not the loudness of the sound, but the metrical structure with accented sounds that elicited larger movement amplitude. The relationship between the stability of coordination and the movement amplitude has been reported in several studies. It was first mentioned by von Holst (1939/1973), and has been supported by several follow up studies (Jirsa et al., 2000; Kudo et al., 2006; Schwartz et al., 1995). Schwartz et al. (1995) revealed that bimanual coordination in the in-phase mode is more stable and induces larger amplitude than in the anti-phase mode in a bimanual coordination task using pendulums. Kudo et al. (2006) also revealed that bimanual coordination is spatiotemporally more stable (the relative phase between two hands is smaller) and induces larger movement amplitude in the double metronome condition than in the single metronome condition. As in these studies, metrical structure with accented sounds has possibly induced larger movement amplitude, as it stabilized the SMS of rhythmic knee flexion-extension movement in upright stance.

4.4.4 Relationship to music

The relationship between the stability of coordination and the movement amplitude is also demonstrated in music research. Van Dyck et al. (2013) recorded people’s dancing behavior toward music in a club-like environment, and investigated the effect of the loudness of the bass drum on the strength of the participants’ synchronization to music, and the activity of their movement. The result indicated that participants more strongly synchronized to music and moved more actively as the loudness of the bass drum increased (Van Dyck et al., 2013). As people typically synchronize the flexion (down) phase, which is the intrinsically stable pattern, with the bass drum, the function of the bass drum (on-beat) and sound that occurs between the bass drum, such as the high-hat (off-beat) in their study could be interpreted as accented (loud) sound and non-accented (soft) sound in our study, respectively. Although it was not directly stated in the paper, the result indicates a strong connection between stronger synchronization to music and higher activity of the movement lead by a louder bass drum (i.e., accented sound). Therefore, as our result is also in line with that of this study, it would be appropriate to suggest that the reason why music has a metrical structure with accented sounds is related to its function stabilizing SMS and increasing the activity of people's movement at the same time.

4.4.5 Functional meaning of music and dance

Finally, the significance of the current study in relation to the evolution of music needs to be discussed. As revealed by a myriad of studies, there is a strong connection between music and body movement (see for review: Levitin et al., 2018), and the importance of this connection to the evolution of music has recently been stated (Richter and Ostovar, 2016). Metrical structure with accented sounds is one important element of music, which can be observed in almost any style of music around the world. The current study indicates that music evolved with metrical structure with accented sounds because it strengthens auditory-motor coupling in terms of entraining body movement to the sound compared to a non-accented sequence. A previous study claimed that one reason music has survived natural selection is because it enhances social bonding, and plays a role as a coalition signaling system (Hagen and Bryant, 2003). Indeed, recent social psychology studies have revealed that sociality, affinity, cooperation, social bond, and reliability are enhanced when people dance in a crowd, or even merely synchronize simple rhythmic movements with other people (Cirelli et al., 2014a, 2014b; Hove and Risen, 2009; Launay et al., 2016; Reddish et al., 2013; Tarr et al., 2015, 2016). Sound has a unique characteristic that it is conveyed to people simultaneously without visual attention. This characteristic enables us to coordinate our movement in synchrony, which means that interpersonal coordination is provided through auditory-motor coupling (or environmental coupling). Therefore, music has possibly evolved with metrical structure with accented sounds in order to encourage people to synchronize with each other and enhance social bonding by strengthening the synchronization between music and people.

Studies in neuroscience also seem to corroborate this idea. Numerous studies have shown that sensorimotor synchronization (Chen et al., 2006, 2008b; Kung et al., 2013) and merely listening to rhythms activate motor regions in the brain, such as the supplementary motor area (SMA), premotor cortex, cerebellum, and basal ganglia (Bengtsson et al., 2009; Chen et al., 2008a; Grahn and Brett, 2007; Grahn and Rowe, 2013; Kornysheva et al., 2010). It is particularly important to note that the SMA and putamen are more activated when an individual listens to a metrically simple rhythm than to a non-metric rhythm or a complex rhythm (Grahn and Brett, 2007; Grahn and Rowe, 2013). This suggests that metrically salient rhythm induces body movement and enhances synchronization by facilitating beat prediction, as the SMA is engaged in the initiation of voluntary movement and the putamen is engaged in beat prediction.

In addition, studies on groove support this idea. Listening to music with a high rating of groove (i.e., the sensation of wanting to move some part of the body when listening to music) (Iyer, 2002; Janata et al., 2012; Madison, 2006) increases activation in the primary motor cortex of musicians (Stupacher et al., 2013). As the rating of groove is shown to increase when the beat is salient (Madison et al., 2011), or when the rhythm has a moderate degree of complexity (Sioros et al., 2014; Witek et al., 2014), a metrically structured sound sequence with accented sound would probably induce a groove sensation that is stronger than that induced by a simple monotonous sound sequence without physical accent. Therefore, it is possible that metrical structure with accented sounds not only stabilizes sensorimotor synchronization, but also increases activation in the primary motor cortex and induces body movement. These findings of neuroscience studies indicating the metrical structure with accented sounds induces body movement and facilitates sensorimotor synchronization also support the idea that metrical structure with accented sounds evolved as an important and widespread musical feature because it facilitates group synchronization by inducing body movement and enhancing people's synchronization towards music.

4.4.6 Limitations

The current study has several limitations. Firstly, I did not include a no-accent condition with soft sounds, which helps exclude the possibility that exposure merely of soft sound contributes to stabilizing the SMS and increases the movement amplitude in the accent conditions. I excluded this condition in order to prevent fatigue in the participants as considering this condition would add two more trials (because there are two starting conditions) in one set and therefore, six additional trials in the entire experiment. This should be investigated in a future study.

Secondly, the task used in this study differed from that of previous studies. As stated previously, SMS studies usually apply finger tapping tasks. However, rhythmic knee flexion-extension movement in upright stance was used in the current study, which prevents us from comparing our results directly with the results of previous studies.

4.5 Conclusion

The present study demonstrated that compared to SMS with sequences without accented sounds, metrical structure with accented sounds stabilizes SMS and induces larger movement amplitude in rhythmic knee flexion-extension movement in upright stance. In addition, I demonstrated that coordination of flexion movement with accented sound is more globally stable than coordination of extension movement with accented sound. Thus, while previous studies have revealed that metrical structure enhances the timing accuracy of sensorimotor synchronization, the current study revealed that metrical structure enhances the global stability of sensorimotor synchronization. As the sound sequence with accented sounds obtained higher groove ratings than the sound sequence without accented sounds, this result indicates that groove has a function of enhancing the synchronization of body movement with the sound sequence, as well as inducing a larger movement amplitude.

Figure 4-1. Participants coordinated their knee flexion movement (A) and extension movement (B) to metronome beats.

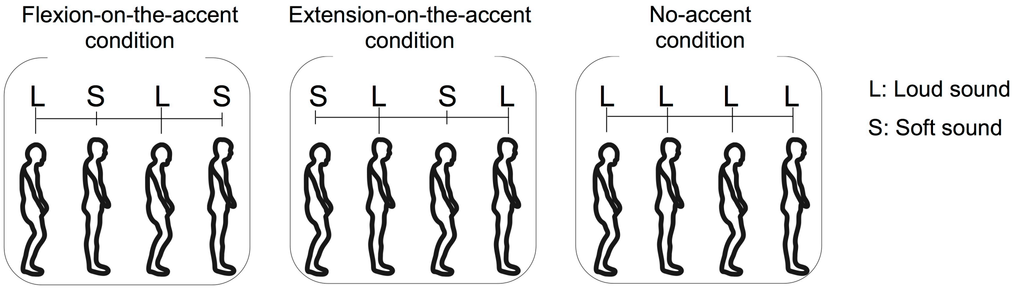


Figure 4-2. Three sound-movement conditions: (1) combining the flexion phase with loud sound and the extension phase with soft sound (flexion-on-the-accent condition), (2) combining the flexion phase with soft sound and the extension phase with loud sound (extension-on-the-accent condition), and (3) combining both phases with loud sound (no-accent condition).

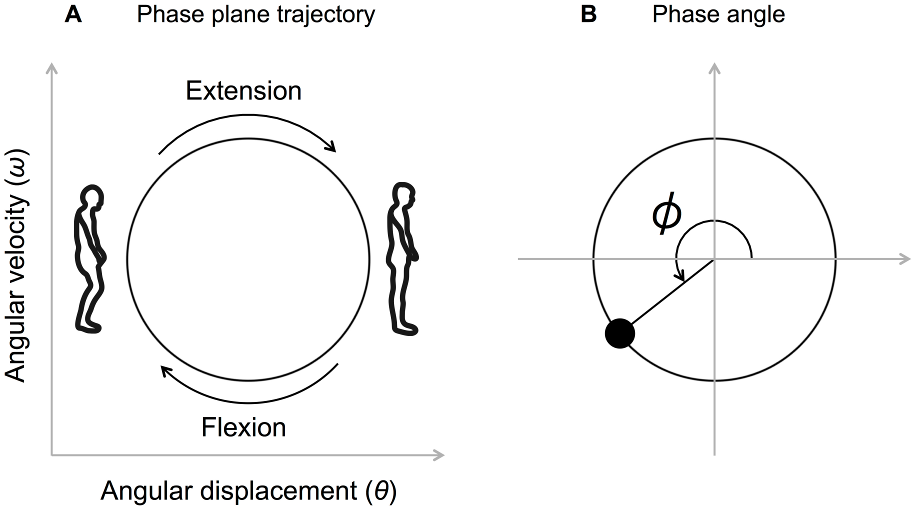


Figure 4-3. Movement trajectory on the phase plane (A) and the definition of the phase angle (B).

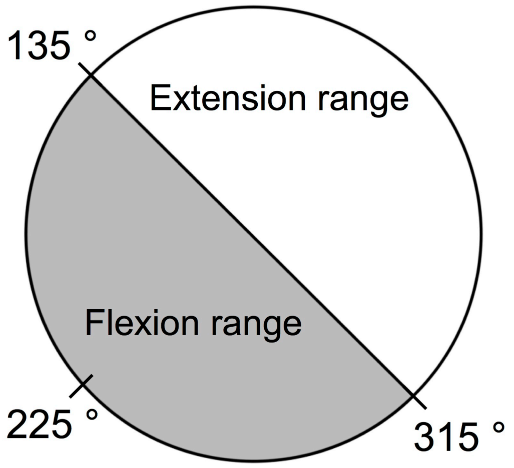


Figure 4-4. The angular displacement and the angular velocity were normalized (Z-scored) between each beat onset. The phase angle defined as $\phi = tan^{-1} \frac{\omega}{\theta}$ at each beat onset was calculated (ω represents the angular velocity, and θ represents the angular displacement). Definition of flexion range and extension range. First, we calculated the mean phase angle of the first 20 beats of all participants, which was 225 degrees. Then, we defined the range of 225 ± 90 degrees (i.e., 135-315 degrees) as the flexion range, and the range of 0-135 or 225-360 degrees as the extension range.

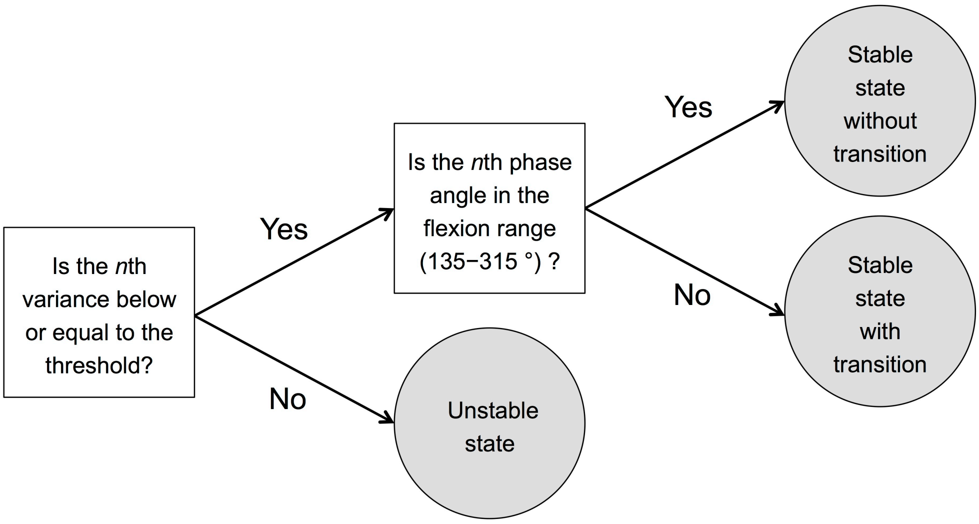


Figure 4-5. Diagram describing the process of dividing each state into three states; (1) stable state without transition, (2) stable state with transition, and (3) unstable state. The threshold was calculated according to the SD of phase angle shown in Miura et al.'s (2010) study whose mean of the circular standard deviation + 2 × between-subject SD was 30 ° (non-dancer at 100 bpm). I set 30 degrees, which is 0.12 in circular variance, as the threshold reflecting the stability of sensorimotor synchronization. The flexion range was set to 135-315 (225 ± 90) degrees because the mean phase angle of the first 20 beats of all participants was 225 degrees.

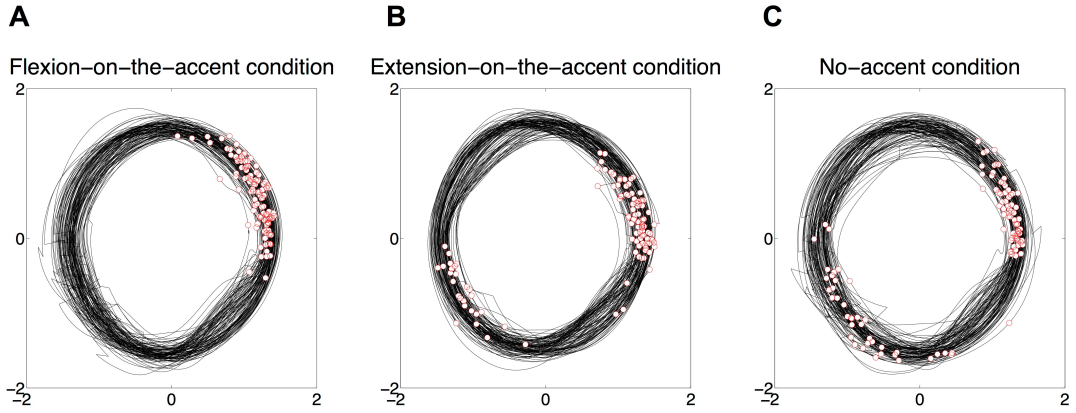


Figure 4-6. A typical example of phase plane trajectory and beat onsets for each sound-movement condition (2.1-7.8 Hz). Beat onsets that need to be synchronized with extension movements are described in red circles. (A) Phase angles are stable for the flexion-on-the-accent condition. (B) A phase transition from extension movement to flexion movement in the extension-on-the-accent condition is observed. (C) Phase angle in the no-accent condition is relatively variable compared to the other two conditions.

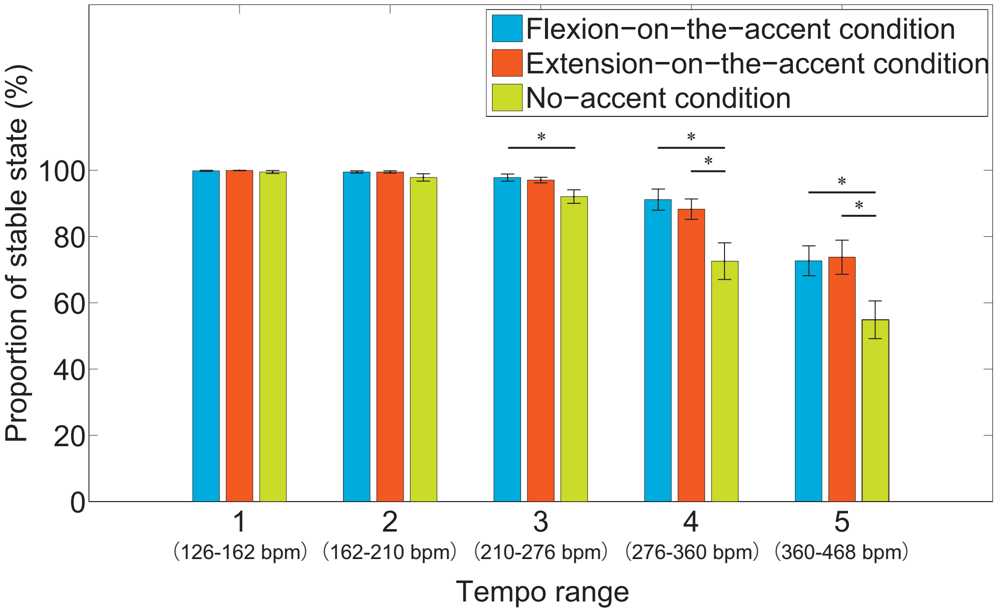


Figure 4-7. The proportion of stable state for each tempo range (* $p < .05$). Tempo range 1, 2, 3, 4, and 5 represents 126-162 bpm, 162-210 bpm, 210-276 bpm, 276-360 bpm, and 360-468 bpm (2.1-2.7 Hz, 2.7-3.5 Hz, 3.5-4.6 Hz, 4.6-6.0 Hz, and 6.0-7.8 Hz), respectively.

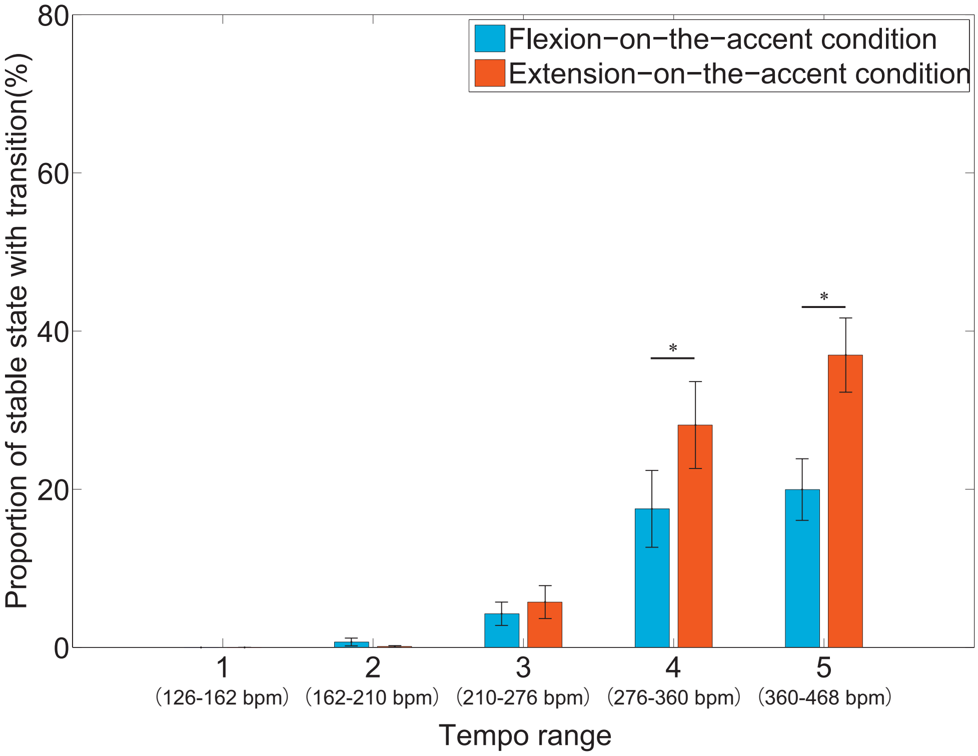


Figure 4-8. The proportion of stable state with transition for each tempo range (* $p < .05$). Tempo range 1, 2, 3, 4, and 5 represents 126-162 bpm, 162-210 bpm, 210-276 bpm, 276-360 bpm, and 360-468 bpm (2.1-2.7 Hz, 2.7-3.5 Hz, 3.5-4.6 Hz, 4.6-6.0 Hz, and 6.0-7.8 Hz), respectively.

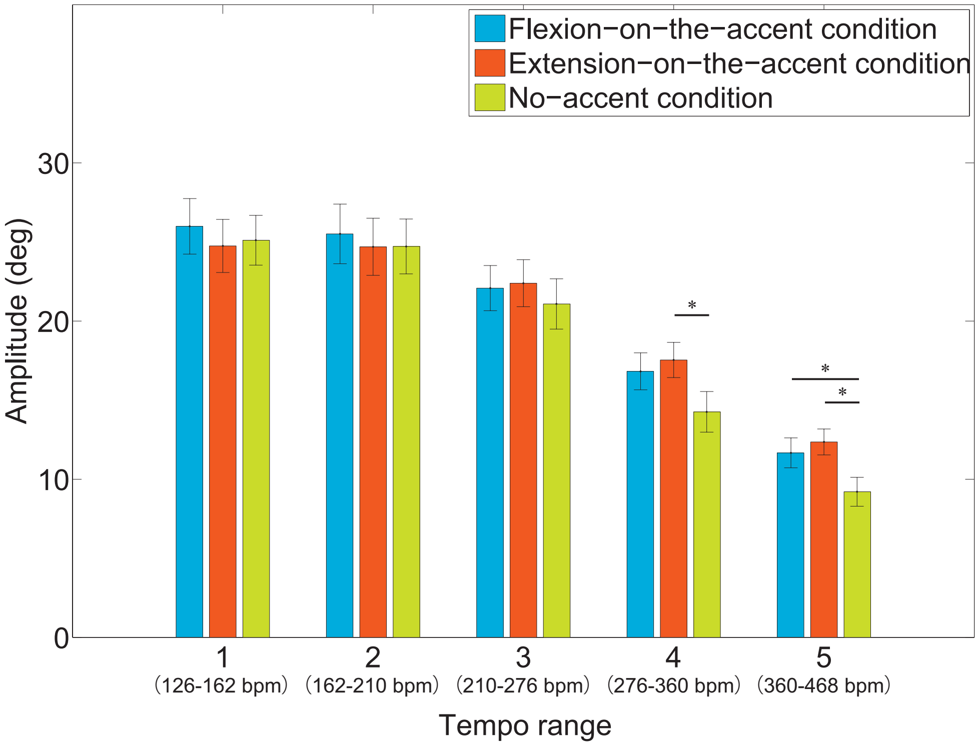


Figure 4-9. The amplitude for each tempo range (* $p < .05$). Tempo range 1, 2, 3, 4, and 5 represents 126-162 bpm, 162-210 bpm, 210-276 bpm, 276-360 bpm, and 360-468 bpm (2.1-2.7 Hz, 2.7-3.5 Hz, 3.5-4.6 Hz, 4.6-6.0 Hz, and 6.0-7.8 Hz), respectively.

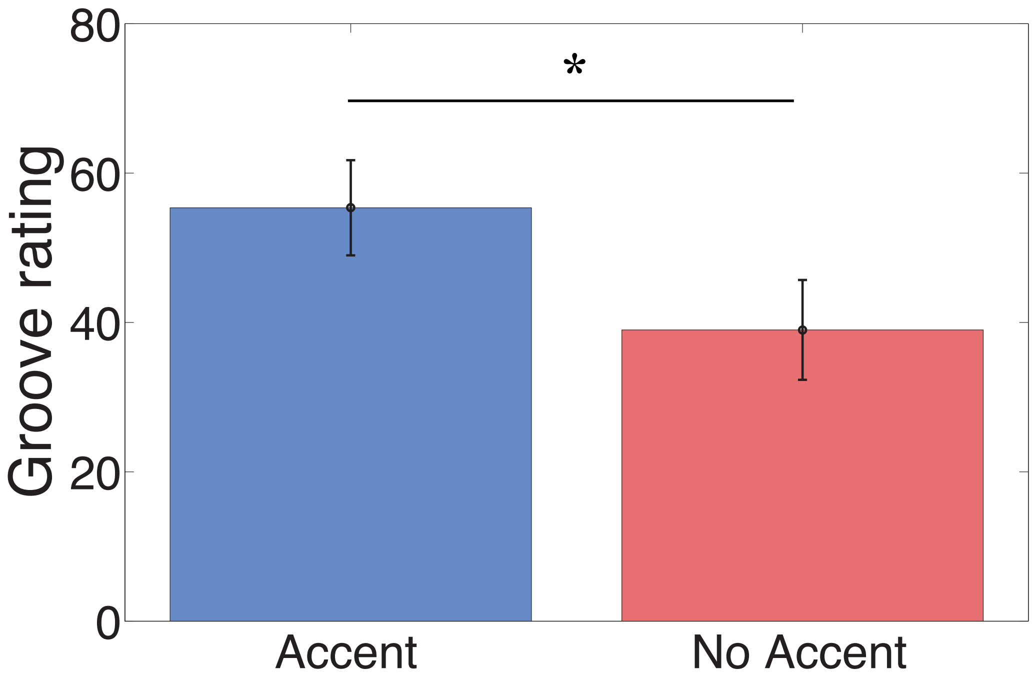
4.6 Supplementary information

4.6.1 Subjective groove ratings of the stimuli

In order to investigate whether a sound sequence with accented sounds has higher groove ratings compared to a sound sequence without accented sounds, a cognitive experiment was conducted in which participants rated the degree of groove of four stimuli. The stimuli were created by combining two accent conditions (accent, and no-accent), and two tempi (240 bpm and 360 bpm). 10 participants rated the degree of groove of four stimuli using a visual analog scale (VAS) ranging from 0 to 100 (0 indicates a low groove rating, and 100 indicates a high groove rating). Groove was defined as “the sensation of wanting to move”.

The result of two-way repeated measures ANOVA revealed that the main effect of accent ($F_{(1, 9)} = 6.77$, $p = .029$, $\eta^2 = .11$) and tempo ($F_{(1, 9)} = 7.16$, $p = .025$, $\eta^2 = .08$) were significant (Supplimentary Figure 4-1). The results indicated that the sound sequence with accented sounds obtained higher groove ratings than the sound sequence without accented sounds, and that 240 bpm obtained higher groove ratings than 360 bpm.

The results validated to use a sound sequence with accented sounds as a sound sequence with groove, and a sound sequence without accented sounds as a sound sequence without groove.



Supplementary Figure 4-1. Groove rating on sound sequence with accented sound (Accent) and sound sequence without accented sound (No Accent) (* < .05).

Chapter 5:
Effect of groove on group synchronization

5.1 Introduction

In chapter 4, I focused on the function of groove entraining movement to sound sequences and investigated whether groove contributes to enhancing the synchronization of body movements to sound sequences. In this chapter, I will focus on another possible function of groove, which is enhancing group synchronization, in order to reveal a new aspect of groove's function.

5.1.1 Evolution of music and its functional meaning

As mentioned earlier, it is reported that music has existed for more than 35,000 years (Conard et al., 2009). Why has music survived for such a long time as one of the most important cultural productions of human beings? Some researchers think that music has no adaptive function, but is merely a byproduct of a culture or language. For example, Pinker (1997) states that the reason we believe that cheesecake delicious is not because cheesecake itself has an adaptive function, but rather, it is a by-product of another fundamental evolutionary reason. In this case, Pinker claims that we enjoy music not because it has an adaptive function, but because it is a by-product of culture or language, which he calls the auditory cheesecake hypothesis. On the other hand, there are also researchers who think that music has adaptive functions, because it has remained central to societies in general for so long (Hagen and Bryant, 2003; Richter and Ostovar, 2016). One hypothesis is that music has the function of strengthening social bonds in a community (Huron, 2001). In fact, music and dance play an important role in various societies as ritual. In addition, because we frequently observe people moving in synchrony to music heard in concerts or other performances in modern society, it is possible that music assists in fostering social bonds within a group.

5.1.2 Effect of moving in synchrony with others

How would music enhance social bonds in a group of people? One of the important features of music is that it induces body movement (Grahn and Brett, 2007; Levitin et al., 2018; Madison, 2006). As seen in concerts, people move their body while listening to music, and as a result, they seem to synchronize with each other. Recently, studies in social psychology have revealed that moving in synchrony with others enhances sociality, affinity, cooperation, social bonds, and reliability (Cirelli et al., 2014a, 2014b; Hove and Risen, 2009; Launay et al., 2016; Reddish et al., 2013; Tarr et al., 2015; Tunçgenç and Cohen, 2016). This indicates that music may enhance social bonds within a group by inducing similar body movements that become synchronized to the music, thus fostering group synchronization.

5.1.3 Groove and synchronization

If this is true, there must be certain aspects that contribute to enhancing group synchronization to music. One possibility is groove. Groove is defined as an aspect of music that makes people want to move (Stupacher et al., 2013). Previous studies have revealed that music with high groove ratings induce body movement more frequently compared to music with low or moderate groove ratings (Janata et al., 2012). In addition, it is reported that music with high groove ratings enhance synchronization with music (Janata et al., 2012; Leow et al., 2014).

If music with a high groove rating enhances people's synchronization with the music, it may also foster synchronization with each other, or group synchronization. In addition, it is reported that music with a clear pulse enhances group synchronization (Ellamil et al., 2016). As salient beats are shown to increase the rating of groove (Madison et al., 2011), this result also suggests that music with high groove ratings fosters group synchronization.

5.1.4 Aims and hypotheses

The current study aimed to investigate the effect of groove on group synchronization. In addition, because a previous study indicated that increased movement was associated with strong synchronization to music (Van Dyck et al., 2013), the effect of groove on movement amplitude was also investigated.

To summarize, I conducted a pseudo-music concert experiment, and investigated whether music with high groove ratings enhanced group synchronization and increased movement amplitude of the audience.

5.2 Methods

5.2.1 Ethics statement

The study was approved by the Ethics Committee of the Graduate School of Arts and Sciences, the University of Tokyo.

5.2.2 Participants

Five volunteers (3 male and 2 female, mean age of 34 ± 11.8) participated in the experiment as audience members. Following oral and written instructions, all participants signed a letter of consent.

5.2.3 Stimuli

Musical excerpts were selected (Table 5-1) based on the groove ratings obtained by a previous groove study (Janata et al., 2012). In order to choose musical excerpts with various groove ratings, the list of music was divided into three groups—high-groove, mid-groove, and low-groove—according to the obtained groove ratings. Next, four musical excerpts were chosen from each group (i.e., twelve musical excerpts in total). Other musical excerpts besides these twelve were also employed in the experiment, but only the data for these twelve excerpts was applied in the analysis.

5.2.4 Data collection

Reflective markers were fixed to participants' foreheads and the parietal region of the head using a cap in order to record their head movements with a motion capture system (NaturalPoint, USA) with the sampling frequency of 100 Hz.

5.2.5 Procedure

The experiment was conducted in a sound proof room. One assistant for the experiment played music using Ableton Live (Ableton, Germany) as a DJ. Participants were told to behave freely as if participating in a live show (Figure 5-1). The experiment lasted about one hour.

5.2.6 Data processing

Thirty seconds of recorded motion data were extracted for each musical excerpt, and the data of the z-axis of the marker put on the parietal region of the head was applied for the analysis. Each data set was band-pass filtered (Butterworth, 0.5-3.0 Hz).

5.3 Results

5.3.1 Correlation between groove rating and degree of group synchronization

For each musical excerpt, the maximum of magnitude-squared coherence (hereafter, coherence) between 1.0-3.0 Hz of each pair was calculated. Next, the mean maximum coherence of all pairs was obtained and employed as the degree of group synchronization for each musical excerpt. Finally, the Pearson's correlation coefficient between the mean maximum coherence and groove rating of each musical excerpt was obtained in order to investigate the relationship between groove and the degree of group synchronization.

The results intimated that there is a significant positive correlation between the mean maximum coherence and groove rating ($r = .59, p < .05$) (Figure 5-2).

The effect of the relationship (acquaintance or non-acquaintance) between participants on the degree of synchronization was also investigated. In the current study, two participants knew each other before the experiment. Therefore, the coherence of this pair (acquaintance pair), and the mean coherence of other pairs (non-acquaintance pairs) were compared. The result suggested that there was no difference in the degree of synchronization between the acquaintance pair and non-acquaintance pairs.

5.3.2 Correlation between groove rating and movement amplitude

The mean movement amplitude of all participants for each musical excerpt was calculated, and then the Pearson's correlation coefficient between the mean movement amplitude and groove rating was obtained. The results showed that there is a significant positive correlation between the mean movement amplitude and groove rating ($r = .66$, $p < .05$) (Figure 5-3).

5.4 Discussion

5.4.1 Summary of results

The current study investigated the effect of groove on group synchronization and movement amplitude. The results revealed that there is a significant positive correlation between coherence and groove rating, as well as between movement amplitude and groove rating.

5.4.2 Effect of groove on group synchronization

The results of the current study indicate that, as hypothesized, groove enhances group synchronization. Previous studies have revealed that music with high groove ratings increase spontaneous body movement, and enhance the synchronization of body movements to music (Janata et al., 2012). This result suggests that groove induces spontaneous body movement and enhances synchronization to music. Our results provided an additional indication that groove enhances synchronization between individuals, or group synchronization.

Previous studies investigating group synchronization via music have shown that music with clear pulses enhances group synchronization (Ellamil et al., 2016). As it is known that clear beats (i.e., pulse) increase ratings for groove (Janata et al., 2012), the reason music with high groove ratings enhanced group synchronization may be related to having clear beats.

5.4.3 Effect of groove on movement amplitude

The results of Van Dyck et al.'s (2013) study suggest that music that enhances people's synchronization with the music and increases body movement. As a significant positive correlation was observed between ratings of groove and movement amplitude, there could be a tight connection between the strength of synchronization and movement amplitude. However, the relationship between them is still not clear. To be more precise, it is unknown whether (1) groove enhanced group synchronization, and therefore movement amplitude increased; (2) groove increased movement amplitude, and therefore group synchronization was enhanced; or (3) groove affected both aspects independently. For instance, visual information is shown to entrain movement (Richardson et al., 2007, 2012) including dancing behavior (Miyata et al., 2017, 2018). This suggests that increased movement amplitude might affect people's behavior in terms of entraining movement, leading to stronger group synchronization. The detailed relationship between synchronization and movement amplitude needs to be investigated in future studies.

5.4.4 Functional meaning of music and groove

The result of the current study suggests that groove, which is defined as an aspect of music that makes people want to move, also contributes to enhancing group synchronization. As stated in the introduction, it is suggested that music and dance together serve an adaptive function strengthening social bonds in a community. As recent social psychology studies have revealed that dancing with others, or merely synchronizing movement with others, enhances sociality, affinity, cooperation, social bonds, and reliability (Cirelli et al., 2014a, 2014b; Hove and Risen, 2009; Launay et al., 2016; Reddish et al., 2013; Tarr et al., 2015), the tentative function of music as strengthening social bonds is probably achieved by inducing body movement and enhancing synchronization of such movements between people. Of course, it may be difficult to believe that a single feature of music could induce body movement, enhance individual synchronization with music, and foster group synchronization, but this is exactly what can be said when considering the results of Janata et al.'s (2012) study with the current one. This states a possibility that groove, which has been considered as an aspect that induces body movement, is a crucial aspect of music that also contributes to strengthening social bonds by enhancing group synchronization (Huron, 2001). Indeed, it is unknown whether group synchronization actually enhanced social bonds in the current experiment. This could be investigated more thoroughly by asking participants about the degree of social closeness felt with other participants using a questionnaire before and after the experiment.

5.4.5 Limitations

Although this study revealed that music with a high groove rating enhances group synchronization and increases movement amplitude, as formerly stated, it is still unknown whether (1) groove enhanced group synchronization, and therefore movement amplitude increased; (2) groove increased movement amplitude, and therefore group synchronization was enhanced; or (3) groove affected both aspects independently. This needs to be examined in future studies. Furthermore, it is still unknown whether the fact that participants shared a common space during the experiment was crucial to group synchronization. In other words, is it possible that the degree of synchronization would be the same even if they were placed in different areas and synchronized to music individually? The effect of sharing the same space on group synchronization needs to be investigated.

In addition, the effect of the relationship between participants on group synchronization needs to be considered in future studies. In the current study, there was no difference in the strength of synchronization between acquaintance and non-acquaintance pairs. However, I cannot exclude the possible effect of current relationships between participants on the degree of synchronization. In fact, a previous study revealed that in a collective ritual, performers and audience members who were related to the performers (relatives or friends) shared heartrate dynamics, whereas performers and audience members who were not related to the performers did not (Konvalinka et al., 2011). This indicates that the similarity of physiological states between participants arising in a collective ritual depends on the relationships between participants. These personal relationships may also affect the degree of behavioral synchronization when listening and dancing to music. I would state this as another problem for future studies to investigate.

5.5 Conclusion

The current study suggests that groove performs the function of enhancing group synchronization, as well as inducing greater movement amplitude.

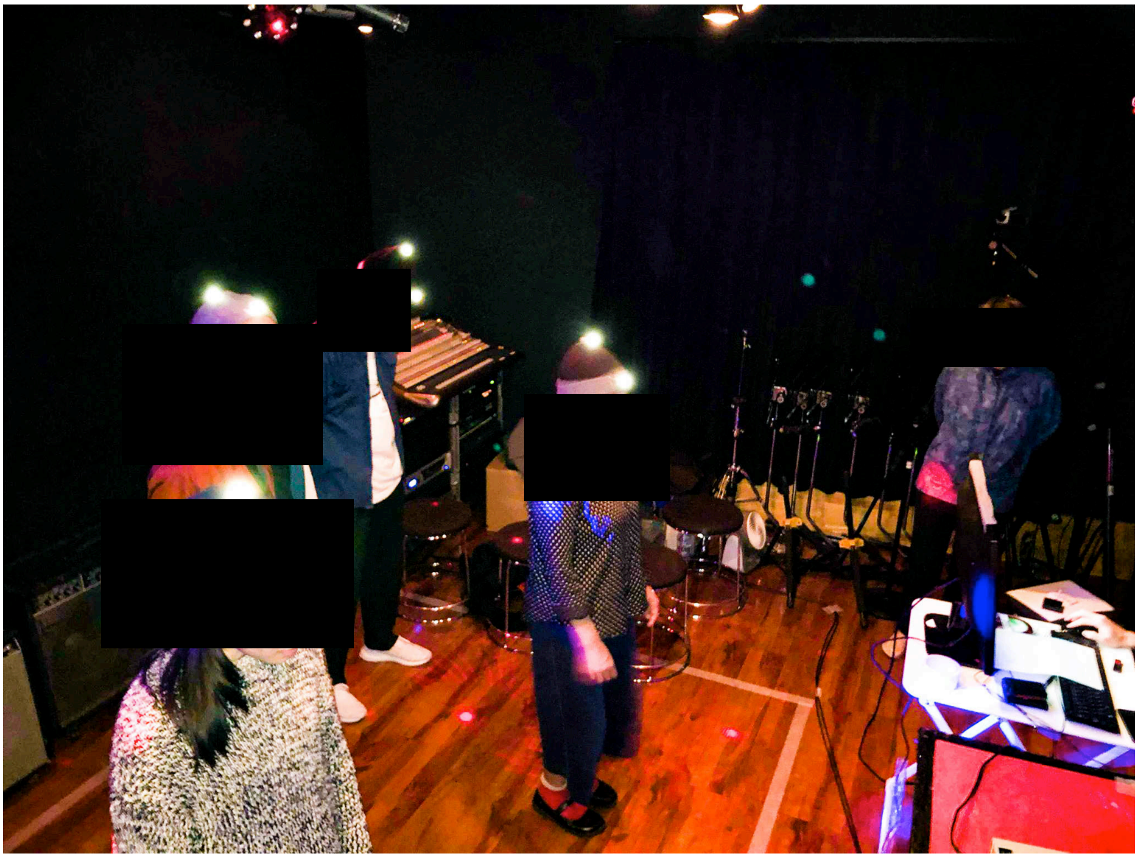


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Figure 5-1. The experiment was conducted in a sound proof room. Participants behaved freely to music as if participating in a music concert.

Table 5-1 Songs used in the experiment

(Groove ratings obtained from previous study (Janata et al., 2012)).

Artist	Song	Groove rating
Ben Harper	Bring the Funk	89.9
Usher	Yeah!	89.7
Destiny’s Child	Lose My Breath	86.4
London Electricity	Fast Soul Music	86.2
Medeski & Martin & Wood	Reflector	76.6
Squirrel Nut Zippers	Hell	73.8
Erin McKeown	We Are More	73.1
Herbie Hancock	Tfs	67.8
Clifford Brown	What’s New?	52.2
James Taylor	Carolina on My Mind	49.0
Jesse Fuller	Raise a Ruckus	46.5
The Gabe Dixon Band	Beauty of the Sea	32.1

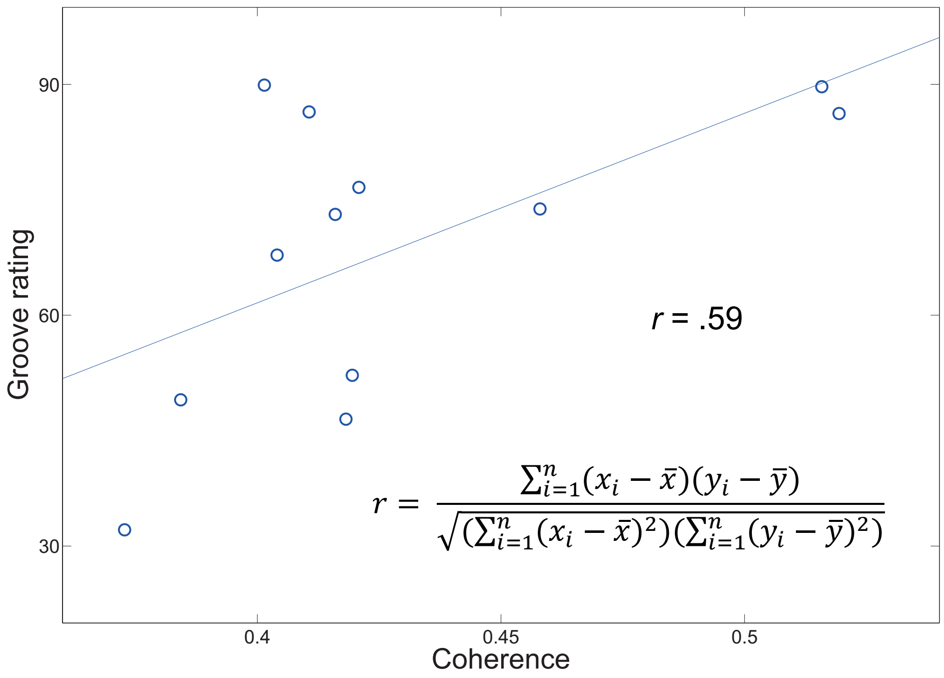

Figure 5-2. Pearson's correlation between groove rating and coherence. Pearson's correlation coefficient is described above, where *x* is groove rating and *y* is coherence.

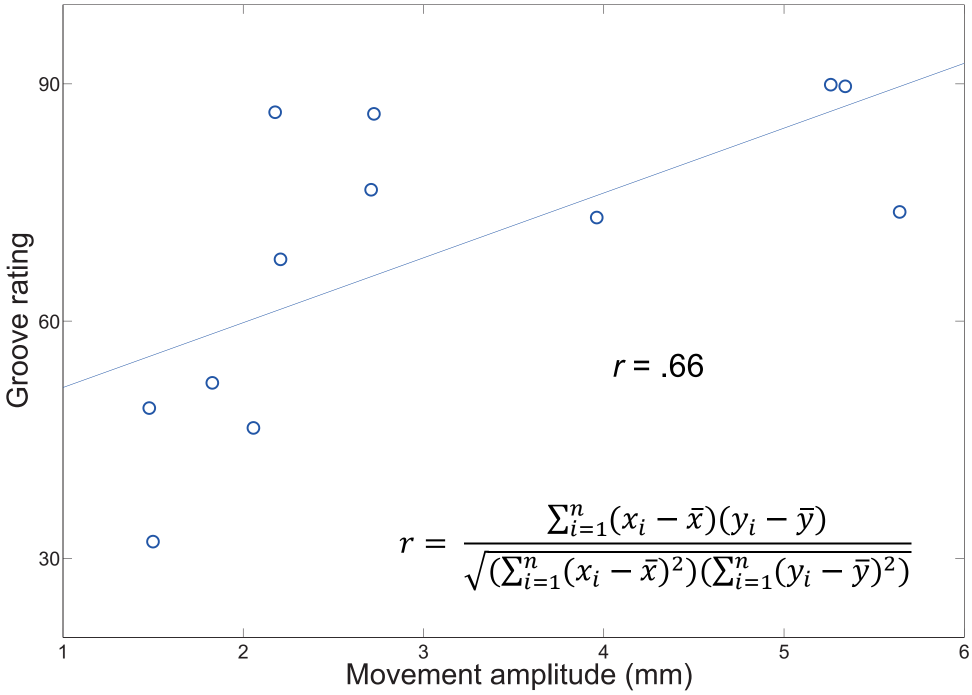

Figure 5-3. Pearson's correlation between groove rating and movement amplitude. Pearson's correlation coefficient is described above, where x is groove rating and y is movement amplitude.

Chapter 6:
General discussion

6.1 Summary of the current study

The current study aimed to investigate the quality of groove by addressing two questions: “Which musical features contribute to creating groove,” and “What are the functions of groove?” More specifically, the relationship between groove and tempo was examined in Study 1, and the relationship between groove and microtiming was examined in Study 2. Next, the effect of groove on sensorimotor synchronization was investigated in Study 3, and the effect of groove on group synchronization was investigated in Study 4.

In Study 1, a cognitive experiment was conducted in order to investigate the relationship between groove and tempo, with the hypothesis that there is an optimal tempo for groove. Participants subjectively rated 30 different drum breaks (5 rhythm patterns × 6 tempi). In order to investigate whether there is an optimal tempo for groove, a linear regression and a quadratic regression was applied setting tempo as the independent variable, and the rating of groove as the dependent variable. Results showed that the quadratic regression model fit significantly better than the linear regression model, and that the second coefficient of the quadratic regression model showed a negative value for every rhythmic pattern. These results indicate an inverted U-shaped relationship between groove and tempo, suggesting that there is an optimal tempo for groove. The estimated range of optimal tempo was 106-127 bpm. In addition, I investigated whether optimal tempo differs among rhythmic patterns by applying a Monte Carlo simulation, but no significant difference in the estimated optimal tempo was observed between any rhythmic patterns.

In Study 2, the relationship between groove and microtiming was investigated through a cognitive experiment applying a paired comparison method using six drum breaks with onset timing of snare drums fluctuating following Gaussian distributions. Participants chose which of two drum breaks has a stronger groove by comparing 15 pairs. The results of the Thurstone scale and binomial test showed that six stimuli can be divided into two groups according to the selection rate: (1) one with small fluctuations that obtains higher groove ratings, and (2) one with larger fluctuations that obtains lower groove ratings. This result indicates that there is an adaptive range of microtiming in which groove is available. This suggests that microtiming is neither important for nor detrimental to groove.

In Study 3, a sensorimotor synchronization experiment was conducted to investigate whether groove contributes to enhancing the synchronization of body movements to sound sequences. A sensorimotor synchronization task was conducted in which participants synchronized rhythmic knee flexion-extension movements while standing upright to a metronome with accented sound (i.e., the accent condition) and one without accented sound (i.e., the no-accent condition). The stability of sensorimotor synchronization was compared between the accent and no-accent conditions according to the variance of phase angle. Results showed that stability in the accent conditions were significantly higher than in the no-accent condition. In addition, the movement amplitude was compared between the accent and no-accent conditions. Results showed that the amplitude in the accent conditions were larger than in the no-accent condition. As a preliminary experiment showed that sound sequences with accented sounds obtained higher groove ratings than sound sequences without accented sounds, this result suggests that groove contributes to enhancing the synchronization of body movements to a sound sequence, as well as to inducing larger movement amplitude.

In Study 4, the effect of groove on group synchronization was investigated by conducting a pseudo-music concert experiment. Musical excerpts with various groove ratings were presented to participants who were instructed to behave freely, as if they were attending an actual music concert. The results of correlation analyses showed a significant positive correlation between groove rating and the average coherence of each pair’s lateral movements, which suggests that groove enhances group synchronization. In addition, there was a significant positive correlation between groove rating and movement amplitude. This indicates that groove increases body movement in addition to fostering group synchronization.

6.2 Implications of the study

In this section, I want to focus on indications about groove made in the current study. I will first focus on the functions of groove and then on its possible relationship to the evolution of music.

6.2.1 Functions of groove

First of all, the current study indicates that, in addition to the function of inducing body movement, as stated in its definition, groove has three additional functions: (1) enhancing the synchronization of body movements to sound sequences, (2) increasing movement amplitude, and (3) fostering group synchronization.

The function of enhancing synchronization of the body's movements has already been demonstrated in a previous study (Janata et al., 2012). Results of the current investigation corroborate these findings. Study 1 indicated that the optimal tempo for groove lies around 107-126 bpm. As 120 bpm is reported to be the tempo at which walking to a metronome becomes most synchronized (Styns et al., 2007), these results suggest that groove is intrinsically related to the degree of synchronization. Furthermore, Study 3 revealed that sound sequences with stronger groove enhance sensorimotor synchronization. In addition, these implications refer to the possibility that groove is not an aspect evoking the desire to move, as generally defined in the literature (Stupacher et al., 2013). Instead, the desire to move when listening to music precedes recognition of groove, because we are entrained to music. In other words, it is possible that groove has the initial function of entraining body movement, which we then interpret as a desire to move created by music, considering groove as a result, or aftereffect which can be explained by post diction (Eagleman and Sejnowski, 2000; Shimojo, 2014).

In addition to the function of enhancing the synchronization of body movement, the current study indicates that groove serves the function of increasing movement amplitude. Study 4 showed that there is a significant positive correlation between the rating of groove and movement amplitude, suggesting that groove contributes to increased movement amplitude. In addition, Study 3 revealed that larger movements were induced in the accent condition (high groove rating) than the no-accent condition (low groove rating), a result that further corroborates the current finding that groove contributes to increased movement amplitude.

Furthermore, fostering group synchronization is also suggested as a function of groove in the current study. Study 4 revealed a significant positive correlation between ratings of groove and the strength of group synchronization. This result indicates that groove serves to enhance group synchronization.

To summarize, the results of the current study indicate that other than inducing body movement, groove has three additional functions: (1) enhancing the synchronization of body movements to sound sequences, (2) increasing movement amplitude, and (3) fostering group synchronization.

6.2.2 Groove and the evolution of music

Next, I want to consider the results of the current study in relation to the evolution of music. First, I want to claim the possibility that groove contributes to strengthening social bonding. The question of how music has survived as such an important cultural product for so long has intrigued many researchers, including Charles Darwin, because music appears to have no obvious adaptive function in helping people survive or flourish (Darwin, 1871). Though the opposing opinion does exist (Pinker, 1997), the hypothesis that music serves the adaptive function of strengthening social bonds within a community is supported by many researchers (Hagen and Bryant, 2003; Huron, 2001; Launay et al., 2016; Richter and Ostovar, 2016; Tarr et al., 2014). As seen thus far, music has multiple functions: inducing body movement, synchronizing movement to sound sequences, and synchronizing people's movements to each other. Since early times, it has been understood that physical synchronization of a group strengthens its cohesion (McNeill, 1995). Furthermore, numerous studies in social psychology have revealed that dancing together, or merely synchronizing movement with others, enhances cooperation, affiliation, and social bonds (Cirelli et al., 2014a, 2014b; Hove and Risen, 2009; Reddish et al., 2013; Tarr et al., 2015, 2016; Valdesolo and DeSteno, 2011; Wiltermuth and Heath, 2009). Taken together, these results suggest that music has a function of strengthening social bond by synchronizing people's movement, by inducing body movement and synchronizing people's movements to music.

This is still a hypothesis, but if true, I wish to declare the possibility that groove is a crucial aspect of music in regards to this function. As groove is defined as an aspect of music that makes people want to move (Stupacher et al., 2013), music with high groove ratings are actually shown to induce body movement (Janata et al., 2012). In addition, previous studies have revealed that groove also contributes to enhancing the synchronization of body movements to music (Janata et al., 2012; Leow et al., 2014). Furthermore, the current study demonstrated that groove also contributes to group synchronization. As the current study did not compare the degree of social closeness of participants before and after the experiment, it is unknown whether social bonds between participants actually increased through group synchronization (Study 4). However, as participants appeared to have better synchronization while listening to music with high groove ratings, and as it can be said that rhythmic synchronization enhances cooperation (Wiltermuth and Heath, 2009), it is possible that music with high groove ratings contribute to strengthening social bonds in a group of people by enhancing group synchronization. Therefore, groove may play an important role in the tentative function of music to strengthen social bonds within the community.

6.2.3 Definition of groove

I would now like to reconsider the definition of groove. Several studies have investigated the concept of groove. In these studies, psychological, behavioral, and neuroscientific research has been applied to define groove as “an aspect of music that makes you want to move.” However, groove is still a vague concept. Here, the validity of this definition of groove is reconsidered.

Firstly, including the quality of induction of body movement in the definition of groove seems to be appropriate according to the current study. Previous studies revealed that participants moved for longer periods of time when listening to music with a high groove rating compared to music with moderate or low groove ratings (Janata et al., 2012). Although I cannot proclaim validity according to the criteria of the previous study, the results of Studies 3 and 4 suggest that groove inducing larger movement could be interpreted as groove induces body movement.

Secondly, it may be appropriate to mention in the definition of groove that induced body movements are related to sound patterns, according to the results of Study 3, which suggests that groove contributes to the entrainment of body movement towards a sound sequence. However, this needs to be examined further in order to include this quality in the official definition of groove.

To summarize, though the concept of groove is still vague, the definition “an aspect of music that makes you want to move” seems to have certain validity. Nevertheless, I will clearly state that it is crucial to keep reconsidering and refining the definition of groove in future studies.

6.2.4 Practical implications

Finally, I want to discuss practical implications of the current study. First, there are some implications for musicians and composers that could be applied when playing instruments and/or composing music. As stated in the introduction, creating groove is one of the most important roles for musicians in popular music, especially for drummers and bass players. Study 2 indicates that there is an acceptable range of variability in microtiming. Therefore, it could be said that it is crucial to play as precisely as possible in terms of timing without large rhythmic deviations in order to create groove. In addition, creating groove is also important for composers, especially for those who create dance music. Study 1 indicates that there is an optimal tempo for groove around 107-126 bpm. This result may be helpful in composing music with high groove ratings.

Furthermore, results of the current study may also be applicable to walking rehabilitation efforts. Study 3 showed that physically accented sound contributes to stabilizing the sensorimotor synchronization of rhythmic knee flexion-extension movement in upright stance to the sound sequence. Various studies have reported that auditory information, such as a metronome beat, is effective for the rehabilitation of walking. Although the current study did not investigate the effect of accent structure on walking, metronome beats with accented sounds may enhance the effect of auditory information on the rehabilitation of walking. Additionally, understanding the benefits of music with groove might be useful to patients with Parkinson's disease, a disorder affecting movement initiation, because groove tends to induce body movement. For instance, creating an auditory stimulus with a tempo of 107-126 bpm might be of help for rehabilitation in terms of walking.

6.3 Problems for the future

The current study pinpointed some important issues needing to be addressed. One is to investigate whether music serves the function of strengthening social bonds in a community. Although interpersonal synchronization of two to three people has been shown to enhance cooperation, it is still unknown whether group synchronization enhances group cohesion. Particularly, investigating whether group synchronization through music can foster social cohesion is an interesting issue that needs to be advanced.

Furthermore, in order to determine whether groove plays an important role in creating social cohesion, we need to directly investigate if music with higher groove ratings fosters group synchronization, and enhance group cohesion at the same time. If confirmed, the hypotheses that music enhances social bonds, and that groove plays a crucial role in this function will be strongly corroborated.

Another interesting issue that needs to be addressed is modeling the groove. Various studies have revealed musical features related to groove (Davies et al., 2013; Etani et al., 2018; Kawase and Eguchi, 2010; Madison et al., 2011; Sioros et al., 2014; Stupacher et al., 2016; Witek et al., 2017). Comparing these results with those of the current study and conducting further experimentation may lead to providing a model that can predict the degree of a piece of music's groove. Additionally, I not only believe that developing such a model to predict groove is possible in the future, but also that a model or algorithm can be developed to help ensure music has a strong groove during the writing process.

In addition, modeling group synchronization of people with music through mathematics is challenging. Group synchronization like the flashing of fireflies (Buck and Bcuk, 1966), chorus of singing frogs (Aihara, 2009; Aihara et al., 2014), and hand-clapping (Néda et al., 2000) are frequently observed phenomena in nature (Strogatz, 2004). It is known that these phenomena can be modeled mathematically using the Kuramoto model, which is a coupled oscillator model (Kuramoto, 1984). Therefore, the Kuramoto model may also be able to describe how people synchronize with music as a group synchronization. The coupled oscillator model has a parameter describing the strength of the coupling between oscillators. As the degree of synchronization between people is correlated with the rating of groove in the current study, if group synchronization through music could be described through the Kuramoto model, the degree of groove might be applied to this parameter, which would further indicate that group synchronization through music can be ensured by following a model of groove, as well.

6.4 Conclusion

This thesis included four studies conducted in order to reveal important aspects of the concept of groove. The results of the current studies suggest that groove performs the functions of enhancing one's synchronization of their body movements to sound sequences, increasing movement amplitude, and fostering group synchronization, in addition to simply inducing body movement.

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