

Influences of rhythmic and spectro-timbral musical features on gait-related movement.

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Tiivistelmä – Abstract Music makes us move, and humans have the universal tendency to synchronise their movements to music. This phenomenon has been used in music therapy to help people with movement disorders regain control over their movements. Rhythmic auditory stimulation has shown promising results in gait rehabilitation in various clinical populations. In healthy populations, various differences have been found between movement while walking to musical and metronome stimuli in terms of stride length. However, insufficient research has been conducted concerning the musical features that could evoke this difference, and which gait-related movements might change under the influence of music. The aim of this motion capture study was to investigate the effects of various rhythmic and spectro-timbral musical features on gait-related movement and to explore the differences between various types of auditory cues and their connections to movement. Participants were asked to walk to a variety of musical and metronome stimuli, which were divided into four tempo groups, ranging from 80 bpm to 145 bpm. Cadence and walking speed tended to increase with tempo, though exact period-matching of cadence to tempo generally did not occur. Furthermore, cadence and walking speed increased with the musical features pulse clarity and spectral flux. Participants also moved more smoothly to slower songs than to moderate tempo songs and fluidity of movement was negatively correlated with pulse clarity, low-frequency spectral flux, and mean spectral flux. Furthermore, stride length and walking speed were increased while listening to metronome beats compared to when listening to musical stimuli and participants tended to adapt their cadence more to the tempi of metronome stimuli than to musical stimuli. Also, musical timing affected hand distance, with decreased hand distance occurring in music with swung timing compared to music with straight timing. These results suggest that musical features can have a significant effect on gait-related movements in young healthy adults.	
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CONTENTS

CONTENTS	4
1 Introduction	5
1.1 Gait assessment	8
1.2 Musical features.....	9
1.3 Music and movement.....	11
1.4 Music and gait	12
1.4.1 Rhythmic cueing in gait rehabilitation	14
1.4.2 Music, metronome, or other cues in gait rehabilitation	15
2 Aims and hypotheses.....	18
3 Methodology	19
4 Methods	21
4.1 Stimuli	21
4.2 Participants	21
4.3 Apparatus.....	21
4.4 Procedure.....	23
4.5 Musical feature extraction	23
4.6 Movement feature extraction.....	24
5 Results	26
6 Discussion	31
References	35
Appendix 1 Song list.....	42

1 INTRODUCTION

Music and rhythm have a profound effect on our movements. This becomes apparent when we nod our heads or tap our feet to a catchy tune, or when we go out dancing. In some cases, music and rhythm can even be used to help people with movement disorders regain control over their movements. In a music therapy intervention called rhythmic auditory stimulation (RAS) (Thaut, 2005), music and simple rhythmic beats (e.g. metronome beats) are used to cue rhythmic movements such as gait with the aim of improving motor control over these movements. This intervention has shown promising results in patients suffering from movement disorders caused by stroke, Parkinson's disease (PD), traumatic brain injury, and other conditions (cf. Thaut & Abiru, 2010).

Though the uses of metronome cues and musical cues in gait rehabilitation have been investigated, few studies have looked at specific musical features that can affect gait patterns. The aim of the current study is to explore the way music and its rhythmic and spectro-timbral features influence gait patterns in young healthy adults. The musical features used in this study have been found to influence movement in an earlier study about dance and music-induced movement (Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2013) and therefore it is hypothesised that these features may also influence gait-related movement. The findings of this study could form a basis for further research on the topic of the uses of music in gait rehabilitation.

RAS is effective because of the rich connectivity between the auditory and motor systems in the human brain (e.g. Bengtsson et al., 2009; Chen, Penhune, & Zatorre, 2008; Chen, Penhune, & Zatorre, 2009; Grahn & Brett, 2007; Grahn & Rowe, 2009; Stupacher, Hove, Novembre, Schütz-Bosbach, & Keller, 2013) and our ability to perceive rhythm and to synchronise our movements to these rhythms. Humans are extremely sensitive to changes in amplitude in sound, making it easy to perceive the pulse of a given piece of music in a remarkably short time, even subconsciously (Parncutt, 1994), typically within two or three repetitions of a pulse (Thaut, 2005, pp. 7, 141). *Pulse* can be defined as a sequence of regularly recurring acoustic events, which create a pulse sensation in response to a musical rhythm (Meyer & Cooper, 1960;

Moelants, 2002; Parncutt, 1994). The *tempo* of a musical piece refers to the number of pulses per minute (measured in beats per minute or bpm), or the rate at which the pulse regularly repeats, that is, the time between two consecutive pulses (measured in inter-onset intervals or IOIs). We can perceive a range of tempi, but there are upper and lower limits to what can still be perceived as tempo. Pulses that are too close together in time are perceived as a continuum, and when the pulses are temporally too far apart, they are no longer seen as a whole and appear isolated. Tempi are perceivable in the range of 30 beats per minute (bpm) to 240 bpm (London, 2012), though the most salient sensations of pulse occur at moderate tempi of around 100 bpm (Parncutt, 1994). Pulse sensations are also most salient when the pulse is highly periodic, such as in electronic dance music, and are less strong when the pulse is less periodic, such as with the use of rubato in Western classical music (Parncutt, 1994). Musical pulses can be subdivided into smaller units (i.e. beats and parts of beats) as well as grouped into larger cycles (i.e. metre), leading to a structure of perceptually stronger and weaker beats (Parncutt, 1994; Yeston, 1976). Within the range of physically perceivable tempi, there are tempi that are easier to move to than others. There is a physical limit to how quickly an action can be successively repeated, and when an action is performed very slowly, it is no longer seen as a string of actions, but rather as a set of unconnected movements. Preferred tempo refers to the periodicity at which it feels most natural to perform a movement. Preferred tempo was long thought to have an average periodicity of 600 ms, or 100 events per minute (Fraisse, 1982). However, a more recent study by Moelants (2002) found that preferred tempo of movement is more likely to be between 120 and 130 events per minute. In line with these findings, the preferred tempo for walking has been found to be around 120 steps per minute (MacDougall & Moore, 2005).

The acts of dancing, tapping along to a song, and walking in time to a rhythmic stimulus are all describing *synchronisation*: the coordination of rhythmic movement with an external rhythmic process, known as the referent (Repp & Su, 2013). Synchronisation occurs in many contexts, but most notably in music performance and dance (Repp, 2005), in which the music acts as a predictable external timekeeper to which movements can be synchronised. If the referent is periodic, as is often the case with music, the predictability of the occurrence of the next event means that it is possible to anticipate when the next event will take place and the following actions can be synchronised with it (Fraisse, 1982). Synchronisation to music can happen spontaneously (Drake, Penel, & Bigand, 2000; Snyder & Krumhansl, 2001), though intention, anticipation, and the will to synchronise arguably play a more pivotal role in synchronisation

(Repp, 2005). Synchronisation can also be suppressed when attention is paid to the stimulus (e.g. at a classical concert), and it is also possible to move off-beat to a rhythmic stimulus (Repp, 2005). Synchronisation to music has been observed in young children (Eerola, Luck, & Toiviainen, 2006) and infants (Zentner & Eerola, 2010), and pulse perception has even been observed in new-borns merely 2 or 3 days after birth (Winkler, Haden, Ladinig, Sziller, & Honing, 2009). These findings suggest that humans may have a predisposition for pulse perception and corporeal synchronisation to a pulse, rather than these being learned traits. Synchronisation with an external rhythm can be measured in terms of period-matching performance and phase-matching performance. The beat period refers to the duration of one beat, and therefore the period-matching performance assesses whether the duration of the movement matches the duration of the beat period. The phase of the beat refers to the temporal location of the beat, meaning that phase-matching performance assesses whether a movement occurs on the beat or not.

Music with a pulse occurs in all human culture in some form or another (Brown & Jordania, 2013; Nettl, 2000), suggesting that humans are wired to perceive and to be influenced by rhythmic sounds. In addition, music has the capacity to influence our movements, and it could be said that music and movement are inseparable (Keller & Rieger, 2009), and in some languages, music and dance are described by the same word (Lewis, 2013). Synchronising behaviours in a group setting (e.g. dancing) is theorised to have improved social bonding in our ancestors (cf. Ravignani, Bowling, & Fitch, 2014; Tarr, Launay, & Dunbar, 2014), and until recently synchronisation was considered a solely human trait (Bispham, 2006; Zatorre, Chen, & Penhune, 2007). However, after the video of the sulphur-crested cockatoo Snowball moving to a pop-song went viral, it shed some light upon the possibility of synchronisation to music not being merely a human ability (Patel, Iversen, Bregman, & Schulz, 2009a; Patel, Iversen, Bregman, & Schulz, 2009b). It was found that Snowball was able to synchronise to music in a range of tempi, though his ability to synchronise is not as sophisticated as that of a human adult (Patel et al., 2009a). It is hypothesised that the ability to synchronise to an external rhythm evolved only in animals that exhibit complex vocal learning (i.e. learning to produce complex vocal sounds through imitation), such as humans, various species of birds, and dolphins (Patel, 2006; Schachner, Brady, Pepperberg, & Hauser, 2009). Other prerequisites for the presence of the ability to synchronise are that the animal should live in a complex social group and should have the ability to mimic nonverbal movement (Patel et al., 2009b).

1.1 Gait assessment

In order to provide the necessary background information for the current study, some basic characteristics of human gait will briefly be explained. For a comprehensive review, see Whittle (2007). Gait can be defined as: the manner or style of walking (Whittle, p. 48) and the gait cycle can be defined as “the time interval between two successive occurrences of one of the repetitive events of walking” (Whittle, p. 52). The gait cycle can be divided into seven phases:

1. Initial contact
2. Opposite toe-off
3. Heel rise
4. Opposite initial contact
5. Toe off
6. Feet adjacent
7. Tibia vertical

(1. Initial contact).

Each stride consists of two double support phases (where both feet are on the ground), consisting of phases 1 and 4 (initial contact of either foot), and two single support phases (where one foot is off the ground). Additionally, each stride can be subdivided into the stance phase (which makes up 60% of one stride), starting at initial contact of one foot (phase 1) and ending with toe off phase of that same foot (phase 5), followed by the swing phase, which lasts from the toe off phase until the next initial contact. See Figure 1 for an overview of the gait cycle.

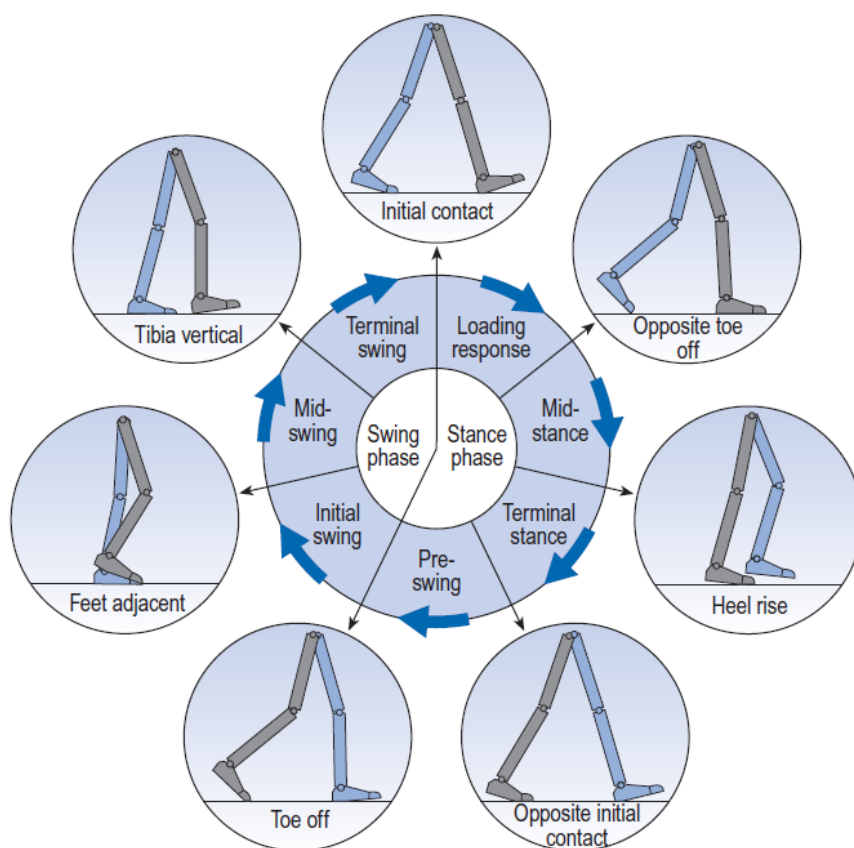


Figure 1. Position of the legs during a single gait cycle by the right leg (grey) (Whittle, 2007, p. 52).

Though there are many ways to describe and assess gait, the most basic objective parameters are cycle time (or cadence), stride length, and walking speed (or velocity) (Robinson & Smidt, 1981). Stride length is the distance between two successive placements of the same foot and consists of two step lengths (Whittle, 2007, pp. 54-55). Cadence is the number of steps taken in a given amount of time, and is usually expressed in steps per minute (Whittle, p. 56). Cycle time, or stride time, is inversely related to cadence, and it expresses the time between the start of one gait cycle and the start of the next (Whittle, p. 56). Walking speed (m/s) is the distance covered by the whole body in a given time (Whittle, p. 56) and is calculated by dividing stride length (in metres) by cycle time (in seconds).

1.2 Musical features

In the current study, the musical features pulse clarity, spectral flux, subband flux, percussiveness, and tempo will be studied. These are rhythmic and spectro-timbral features of music that have previously been shown to be embodied in dance movements (Burger et al.,

2013) and therefore it is hypothesised that these features may be correlated with gait-related movements too. In this chapter, a brief overview of the aforementioned musical features and their connections to movement will be discussed.

Pulse clarity is a high level musical feature which conveys the ease with which a listener can perceive the underlying pulse of a musical piece (Lartillot, Eerola, Toiviainen, & Fornari, 2008). Pulse clarity has been found to be embodied in the whole body during dance (Burger et al., 2013) and is likely to induce periodic movements at the beat level in music (Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2014). To computationally determine the pulse clarity of a given musical piece, the first step is to create an onset detection curve based on either the amplitude envelope, spectral flux, or pitch of the signal. Then, pulse clarity can be estimated based on the autocorrelation curve (Lartillot et al., 2008), which is acquired by correlating the signal with itself at different points in time to find periodicities.

Spectral flux shows changes in the spectrum of an audio signal over time (Lartillot, Toiviainen, & Eerola, 2008) and *subband flux* represents the changes in spectrum over time within a set range of frequencies called subbands. With subband flux the entire audio signal is divided into multiple subbands and the spectral flux within these subbands is extracted separately. It has been found that high spectral flux in the lower channels between 50 and 200 Hz (subbands 2 & 3) are correlated with the perception of fullness in music, whereas in the higher channels at 1600-6400 Hz (subbands 7 & 8) this represents perceived activity (Alluri & Toiviainen, 2010; Alluri et al., 2012). In research related to music-induced movement, Burger and colleagues (2013) found that low frequency spectral flux was mostly embodied in the form of fast head movements, and that high frequency spectral flux can be embodied through fast movements of the head and hands, a large distance between the hands, and an increased amount of total movement.

Percussiveness represents the average attack slope of all onsets. For musical stimuli containing a high number of percussive elements, people have been found to move their centre of mass, head, and hands faster, have a larger distance between their hands, use an increased amount of movement, and wiggle their shoulders more (Burger et al., 2013). Characteristics of the attack phase can be extracted from the amplitude envelope of an audio signal, wherein the local maxima indicate the position of the end of the attack phase and the start of the attack phase by

the local minima (Lartillot et al., 2008). The resulting slope between these two values gives the main attack slope which indicates how perceptually percussive a given musical piece is, with steeper attack slopes meaning that the piece is more percussive.

1.3 Music and movement

There is rich connectivity between the auditory and motor system of the human brain, and therefore it is not surprising that people tend to move to music spontaneously (Lesaffre et al., 2008). Music-induced movement can be influenced by multiple factors, such as some physical features of the music itself, the emotional content of the music, the personality of the listeners, and the context in which the listeners find themselves. Music can motivate people during exercise, not only improving their mood, but also lowering perceived exertion, improving energy efficiency, and increasing work output (Karageorghis & Priest, 2012). However, the specific musical features that influence movement and physiological processes in the listener are not fully understood. As a follow-up to chapter 1.2, an overview of some other aspects of music and their relation to movement will be explained here.

Investigations into the *groove* of the music, defined as musical aspects that make people want to move to music (Madison, 2006), have found that syncopation is an important factor in defining the groove (Witek, Clarke, Wallentin, Kringelbach, & Vuust, 2014). Witek and colleagues found that drum patterns with a medium amounts of syncopation make people want to move to music more than excerpts with either no syncopation or high amounts of syncopation. Groove may also be related to spectral flux, as spectral flux in high and low frequencies has been found to make people want to move to music (Burger, Ahokas, Keipi, & Toiviainen, 2013). Furthermore, fast music and music from the genre soul/R&B are generally rated to have groove (Janata, Tomic, & Haberman, 2012). However, as groove reflects the propensity or will to move to a certain piece, it does not necessarily reflect the actual movements of listeners to a certain stimulus.

A number of studies have investigated spontaneous or quasi-spontaneous movement, usually in the form of dance, to music. As mentioned in chapter 1.2, the musical features pulse clarity, subband flux, and percussiveness have been linked to various types of movement. At a more basic level, metre and the metrical levels in music have been found to be embodied in movement

(Toiviainen, Luck, & Thompson, 2010). With music in 4/4 time, vertical movements were found to occur at tactus level, whereas mediolateral movements were mostly embodied at the four-beat level, and faster metric levels were embodied in the extremities, whereas slower metric levels were embodied in the central parts of the body. (Toiviainen et al., 2010). Another study found that the dynamic strength of the bass drum in music affects people's dance movements (Van Dyck et al., 2013). A prominently present bass drum part can induce faster and shorter movements, which are most visible in the hips, compared to music where the bass drum is less pronounced (Van Dyck et al., 2013).

The emotional content of music has also been found to influence movement (Burger, Saarikallio, Luck, Thompson, & Toiviainen, 2013). Burger and colleagues found that participants tended to increase their rotation range to pleasant and happy music, and tended to decrease their rotation range to music expressing anger, as well as using more complex movements with happy music and less complex movements with sad music. Additionally, participants moved more fluidly to pleasant and tender music, and less so to active music (Burger et al., 2013). Fluidity (or circularity/smoothness) of movement is defined as the ratio between velocity and acceleration of mocap data (Burger & Toiviainen, 2013; Burger et al., 2013). The findings of these studies suggest that the participants may have (subconsciously) used their bodies to express and reflect the emotional content of the musical pieces. In contrast, if emotion is induced in the listener rather than expressed in the music, participants will move differently to emotionally neutral music, depending on whether happy or sad emotions were induced (Van Dyck, Maes, Hargreaves, Lesaffre, & Leman, 2013). Van Dyck and colleagues found that in the happy condition, their participants moved faster and with more acceleration, and made larger and more impulsive movements than those in the sad condition.

1.4 Music and gait

Music and its rhythm can be used in rehabilitation to help people with various neurological disorders regain control over their movements while walking. However, to fully understand the effects of music on movement and its benefits within rehabilitation, it can be useful to first investigate healthy populations and the effect that music has on their walking patterns. This chapter will focus first on healthy participants and the effects of gait cueing on gait-related

movement, second on the uses of gait cueing in clinical populations, and finally on various types of cues that may be used in gait rehabilitation.

Studies have found that stride length can be increased when listening to music compared to when listening to metronome beats in healthy adults (Styns, van Noorden, Moelants, & Leman, 2007; Wittwer, Webster, & Hill, 2013a). Another study found that walking speed increased (due to increases in stride length) while listening to active music and decreased while listening to relaxing music, compared to the baseline condition where participants listened to metronome beats (Leman et al., 2013). These findings suggest that there are certain musical features that can “activate” or “relax” people while walking, even if the tempo of the music remains the same.

It has been shown that people are capable of synchronising their footfalls to the beat of music at tempi ranging from 50 bpm (beats per minute) and 190 bpm when instructed to do so (Styns et al., 2007). If no specific instructions to synchronise are given, participants generally will not synchronise to rhythmic auditory stimuli while treadmill walking (Mendonça, Oliveira, Fontes, & Santos, 2014). However, a study where participants were walking in an outdoor urban environment found that, without being given explicit instructions to synchronise, participants’ cadence and walking speed were still affected by the tempo of the music (Franek, van Noorden, & Rezny, 2014). Though participants did not exactly synchronise their cadence to the beat of the music, their cadence and walking speed decreased with slower music and increased with faster music, and they walked faster while listening to music than while walking without music (Franek et al., 2014).

The tempo of a musical piece can also influence running cadence when the tempo is increased or decreased imperceptibly compared to the original stimulus (Van Dyck et al., 2015). Running differs from walking in that the double support phase is omitted and an additional flight phase occurs, in which neither foot is on the ground (Whittle, 2007, p. 54). Van Dyck and colleagues’ findings suggest a spontaneous shifting of running cadence towards the tempo of a piece when the manipulation of tempo is unnoticeable.

1.4.1 Rhythmic cueing in gait rehabilitation

Music and other auditory rhythmic stimuli have been used to facilitate recovery of gait in patients with movement disorders due to acquired brain damage, Parkinson's disease (PD), or other causes. As part of neurologic music therapy, Thaut (2005) proposed an intervention known as rhythmic auditory stimulation (RAS) which can be used to facilitate rehabilitation of rhythmic movements, such as gait, through the use of rhythmic auditory cues (RACs). RAS uses RACs in 2/4 and 4/4 meter, presented either as metronome beats or as strongly accentuated beats in complete musical patterns (Thaut, 2005). Because of the predictability of the beat in music and our ability and tendency to synchronise with that beat, music and other rhythmic sounds can be used to cue gait: a movement which is intrinsically and biologically rhythmic. RAS and other music-based movement therapies are promising interventions because they are inexpensive (Wittwer, Webster, & Hill, 2013b) and they combine cognitive movement strategies, cueing techniques, balance exercises, and physical activity (De Dreu, Van Der Wilk, Poppe, Kwakkel, & Van Wegen, 2012).

In stroke patients, RAS has been found to improve gait-related movement. In hemiparetic stroke patients, improvements in the symmetry of the patients' stride times were found after three sessions of RAS training, as well as increased stride length and increased weight bearing time on the paretic side (Thaut, McIntosh, Prassas, & Rice, 1993). Later studies have found improvements in walking speed and stride length after RAS compared to conventional physical therapy (Thaut, McIntosh, & Rice, 1997) and improvements in walking speed, stride length, cadence, and gait symmetry compared to neurodevelopmental therapy less than three weeks post-stroke (Thaut et al., 2007). Furthermore, walking to rhythmic stimuli can increase arm swing and stride length in post-stroke patients (Ford, Wagenaar, & Newell, 2007) and improve balance and stability (Suh et al., 2014). A best-evidence synthesis by Wittwer, Webster, and Hill (2013b) showed moderate evidence of improvement in walking speed and stride length in individuals suffering from stroke after gait training with rhythmic music. These findings demonstrate that, though the intervention is promising, more studies with high methodological quality are needed to assess the effectiveness of RAS for patients with stroke.

In patients suffering from PD, gait and balance can be impaired due to various symptoms, including tremors, muscle rigidity, increased cadence and decreased stride length, shuffling gait, decreased arm movement, and freezing of gait due to the inability to initiate certain

movements (Gonzalez-Usigli, 2015). In one of the first trials on the topic of RAS by McIntosh and colleagues (1997) it was found that RAS improved walking speed in PD patients with and without medication due to their larger stride length post-intervention. Improved walking speed, stride length, and cadence were also seen in a longer-term training program (Thaut, McIntosh, Rice, Miller, Rathbun & Brault, 1996). Later trials also confirmed the findings that RAS can increase cadence, stride length, and walking speed (de Bruin et al., 2010; Hausdorff et al., 2007), as well as decrease gait variability (del Olmo & Cudeiro, 2005). Arias and Cudeiro (2010) found that RAS with metronome stimuli at 10% above preferred cadence tempo could reduce freezing of gait.

RAS has mostly been studied with patients suffering from the consequences of stroke or PD, and studies concerning the use of RAS with other patient populations are few (for a review, see Wittwer et al., 2013b).

1.4.2 Music, metronome, or other cues in gait rehabilitation

Studies into RAS have used various stimuli (usually music or metronome beats), though there has been limited investigation into optimal cue types (Wittwer et al., 2013a). This chapter aims to explore the possible uses of naturalistic music, artificially created music, metronome stimuli, and other rhythmic auditory stimuli in therapeutic settings.

Naturalistic music refers to pre-existing or “real-world” music which includes all the features that are commonly in music we listen to in daily life. Naturalistic music can be used in studies to observe emotion induction because of its high ecological validity, though with these stimuli it is difficult to control musical or acoustic parameters (Eerola & Vuoskoski, 2013). In contrast, artificially created music allows researcher to control various musical parameters, though these manipulation schemes are not always sufficiently controlled (Eerola & Vuoskoski, 2013). Furthermore, artificially created stimuli do not have all the features commonly found in music that allow people to integrate all the components of musical information into one perceptual *Gestalt* (Leaver, Van Lare, Zielinski, Halpern, & Rauschecker, 2009). Naturalistic and artificial music evoke different brain responses in listeners (Abrams et al., 2013) suggesting that artificial music does not reliably represent music as it is heard in daily life.

In studies on the subject of RAS, some studies have used artificially created music to control for motivational qualities of music (e.g. Thaut et al., 1996), because repetitive use of low-complexity music has been shown to reduce arousal and feelings of motivation (Berlyne, 1971). The ease of implementation into therapeutic settings and the control over the stimuli are attractive reasons to use artificially created musical stimuli. However, as mentioned by de Dreu and colleagues (2012), naturalistic music has many benefits over synthesised music or pure rhythmic stimuli which could be used in therapeutic settings. The enjoyment of music can cause physiological pleasure sensations (Blood & Zatorre, 2001), can distract the patient from sensations of fatigue (Lim, Miller, & Fabian, 2011), and the motivational qualities of music can increase therapy compliance (De Dreu et al., 2012). Furthermore, motivational music can increase endurance during exercise tasks, whereas a version of the same song with only rhythm instruments does not have the same effect (Crust & Clough, 2006). Thaut (2005, pp. 146-147) states that the emotional-motivational qualities of rhythm and music are desirable in therapy if the musical elements enhance rhythm perception, the music is familiar and preferred by the patient, and if the patient can perceive complex sound patterns and will not get confused. The perception of very slow beat patterns may be enhanced by regularly occurring musical information between the beats (Thaut, p. 147).

Only a few studies about RAS have used natural music stimuli to cue gait in clinical practice, and no significant differences between cue types have been found so far in patients with advanced dementia (Clair & O'Konski, 2006) or Huntington's disease (Thaut, Miltner, Lange, Hurt, & Hoemberg, 1999). However, in healthy adults, some differences between musical stimuli and metronome beats have been found. In healthy older adults, walking to a march by Elgar was found to evoke longer strides and, by extension, faster walking speed compared to walking to metronome beats (Wittwer et al., 2013a). Naturalistic music has been found to evoke both shorter and longer strides compared to metronome beats, depending on the relaxing or activating qualities of the music (Leman et al., 2013).

In recent years, the RAS intervention is being expanded by the introduction of interactive systems using digital technology, allowing for on-the-fly adaptation of the auditory stimuli to the gait patterns of the patients. An interactive, adaptive cueing system was found to reinstate healthy gait patterns in PD patients and to increase the experience of stability compared to fixed-tempo RACs (Hove, Suzuki, Uchitomi, Orimo, & Miyake, 2012). The same adaptive

cueing system was found to improve gait symmetry and the timing of footfalls in hemiparetic stroke patients: a result that was not achieved using fixed-tempo stimuli (Muto, Herzberger, Hermsdoerfer, Miyake, & Poeppel, 2012). Rodger, Young, and Craig (2014) describe a cueing system in which the swing phase of the PD patients can be sonified in real-time aided by a motion capture system. Furthermore, human action sounds (in this case: the sound of footsteps on gravel) were also used to cue gait, using information from force plates (Rodger et al., 2014). Both sonifying methods led to improvements in step length variability. Rizzonelli (2016) studied a musical feedback system in which more instruments are added to a rhythmic stimulus depending on the stride length of the patient as a “reward” for increasing stride length. The results could suggest increased stride length in PD patients when training with the musical feedback system compared to traditional RAS (Rizzonelli, 2016).

In conclusion, it is not clear which cue types are optimal for rhythmic cueing of gait. However, there is some evidence to suggest the possibility of music either activating or relaxing people while walking, though the mechanism driving these changes is not clear. Furthermore, the motivational and emotion-inducing effects of music may be reasons to use music in therapy. Finally, adaptive and interactive systems could be feasible and effective methods to cue gait, though further research is needed on this topic.

2 AIMS AND HYPOTHESES

The current study aims to investigate the relationship between musical features and movement features with possible implications for clinical practice. The studied movement features are relevant in the context of gait rehabilitation, as they can be symptoms of pathological gait. The basic gait parameters cadence, stride length, and walking speed may be severely impaired in people with PD (Morris, Iansak, Matyas, & Summers, 1996; Murray, Sepic, Gardner, & Downs, 1978) and patients who have suffered from stroke (von Schroeder, Coutts, Lyden, & Nickel, 1995). Furthermore, arm swing is a frequently reported motor dysfunction in patients with PD (Nieuwboer, Weerdt, Dom, & Lesaffre, 1998), and smoothness of movement may be disrupted after stroke (Rohrer et al., 2002). Therefore, improvement of these movement features could be desirable outcomes of treatment for people suffering from movement disorders. Due to the lack of studies covering the topic of musical features and gait-related movements, this study is exploratory in nature and no specific hypotheses can be formulated. However, it can be expected that the musical features will affect gait-related movement, as the studied features have been linked to music-induced movement in a previous study (Burger et al., 2013). Burger and colleagues found that high-frequency spectral flux and percussiveness were related to a larger distance between the hands, therefore increased arm swing during gait can be expected with these features. It is also expected that cadence will increase with faster tempi and decrease with slower tempi, and period-matching may not occur, similarly to what was found by Franek, van Noorden, and Rezny (2014), who did not give instructions to synchronise. The phase matching performance of cadence will not be assessed in the current study, because period matching has been found to be a more reliable measure of synchronisation (Thaut & Kenyon, 2003). Furthermore, the current study aims to compare different cue types on movement, specifically: naturalistic music and metronome cues. Optimal cue types have not been studied sufficiently, but based on the available literature (Styns et al., 2007; Wittwer et al., 2013a) it is hypothesised that stride length will be increased with musical stimuli compared to metronome stimuli.

3 METHODOLOGY

To analyse human movement, it is necessary to use devices that record these movements accurately. Movement can be recorded optically, through assessment of still pictures or video recordings, or non-optically by measuring orientation, acceleration, or force. Non-optical systems include inertial, magnetic, and mechanical systems. Inertial systems measure acceleration and orientation/rotation through accelerometers, gyroscopes, and magnetometers. In magnetic motion capture systems, electromagnetic sensors measure the orientation and position of the joints of a person in relation to the signal of a transmitter. In mechanical motion capture systems, the person wears an exoskeleton through which body joint angles can be tracked. Optical motion capture data can be represented in 2 dimensions (on a plane) or in 3 dimensions (in a space). 3-dimensional optical motion capture systems are used to create 3D digital representations of an actor or a moving object, after which it is possible to analyse the movements in great detail. These systems are frequently used in entertainment for animation purposes and in life science for research or diagnosis. 3D optical systems can use passive markers, active markers, or no markers, and acquire data through image sensors (i.e. cameras) and use triangulation to pinpoint the location of an object of interest (e.g. a marker). These systems deliver data in 3 degrees of freedom (3DOF), that is, in the three dimensions of space on the X, Y, and Z axes. Data may also be given in 6 degrees of freedom (6DOF), which, in addition to the spatial data, includes information about rotation angles in 3 dimensions.

Optical systems with passive markers, as used in the current study, use cameras that detect light to determine the 3D locations of reflective markers. These reflective markers are attached to strategic body parts, usually where joints are located, either by attaching the markers to a special mocap suit with Velcro, or directly to the skin using adhesive tape. The cameras are adjusted so that they only pick up the bright reflections from the markers, ignoring less reflective surfaces such as skin and fabric. Optical motion capture systems require direct visibility of the markers, meaning that if a marker is hidden (e.g. behind other body parts or clothing) it will not be recorded. This is almost inevitable, and while walking especially the hip markers are at risk of being covered by the arms or hands. These instances in which a marker temporarily disappears from view can be alleviated by using linear interpolation (Burger & Toiviainen,

2013), which takes the last frame in which the marker is seen and the first frame where it appears again and “connects the dots.”

4 METHODS

4.1 Stimuli

Participants were presented with thirty-six randomly organised 30-second stimuli. Thirty-two of the stimuli were musical excerpts of pre-existing songs and pieces, and four consisted of metronome beats (see Appendix 1 for the full list of musical stimuli). The musical stimuli fit into one of four tempo groups: 80-85 bpm, 100- 105 bpm, 120-125 bpm, and 140-145 bpm (hereafter: tempo group 1, 2, 3, and 4, respectively). Within each tempo group a variety of genres was represented, namely: classical, jazz, electronic, and pop/rock. All stimuli were in 2/4 or 4/4 time, though they differed in their timing (i.e. whether the music was in swung or straight timing). The metronome stimuli consisted of the sound of a snare drum and were set to the following tempi: 80 bpm, 100 bpm, 120 bpm, and 140 bpm, thus corresponding to the tempo groups of the musical stimuli.

4.2 Participants

A total of 25 healthy young adults took part in the study. Five participants were excluded due to missing data, leaving a total of 20 participants (12 females, mean age 26.79, *SD* of age 3.94) to be included in the final analysis. Eight participants identified themselves as semi-professional or professional musicians, eight as amateur musicians, and most ($N = 19$) had learned to play an instrument at some point in their lives. Fourteen participants reported to practice sports once a week or more and two participants had had formal dance training within the last twelve months. Participation in the study was rewarded with a cinema ticket voucher.

4.3 Apparatus

Participants' movements were recorded with 8 Qualisys Oqus 5+ cameras mounted on the walls around the capture space at a height of 2.5 to 3 metres. Four additional cameras mounted on tripods at a height of approximately 2 metres were used to capture the space in the corner of the lab, at the participants' starting position. Figure 2 shows the camera locations in the capture

space. The system was tracking at a rate of 120 Hz. The lab was set up to make the walkway as long as possible, meaning that the participants would start walking at the edge of the room and walk diagonally across the room to the far corner, making the walkway approximately 10 metres in length. A total of 28 markers were used, the locations of which are shown in Figure 3A. Most markers were attached to a mocap suit, with the exception of the finger markers (markers 19 & 20) which were attached to the skin of the middle finger with double-sided tape, and the heels (25 & 26) and big toes (27 & 28), which were attached to the socks with double-sided tape. The stimuli were played in random order through speakers using Max 7 software. The sound in the room was recorded for reference purposes using two overhead mics at a height of approximately 2.5 metres. The output from the microphones, the audio signal from the playback, and the audio signal emitted by the Qualisys cameras, were recorded using ProTools.

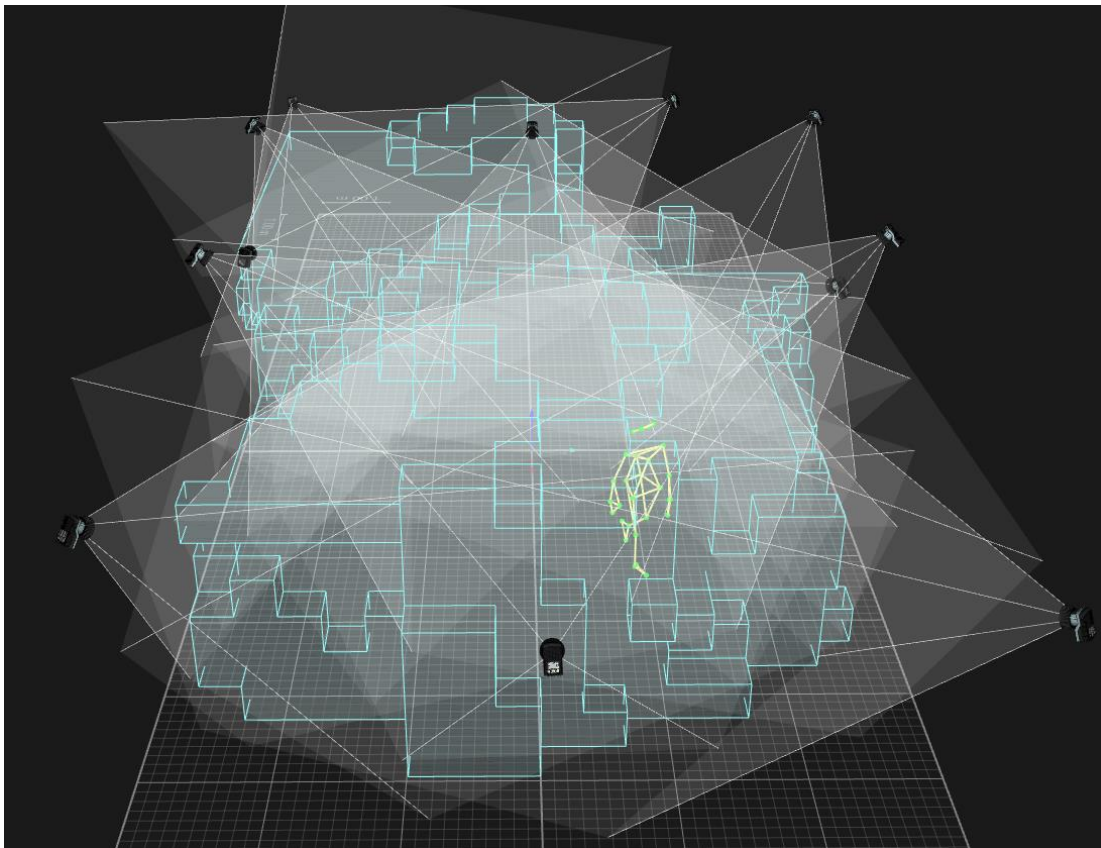


Figure 2. A representation of the capture space, showing the camera locations, the camera cones, and the covered volume after calibration (in turquoise). The starting point for walking is in the top left corner.

4.4 Procedure

The data were recorded in the motion capture lab at the Music Department of the University of Jyväskylä (Finland). Participants were recorded individually, and were instructed to walk naturally to the songs or metronome stimuli, as if they were walking somewhere and they would hear this stimulus being played on their own portable music player.

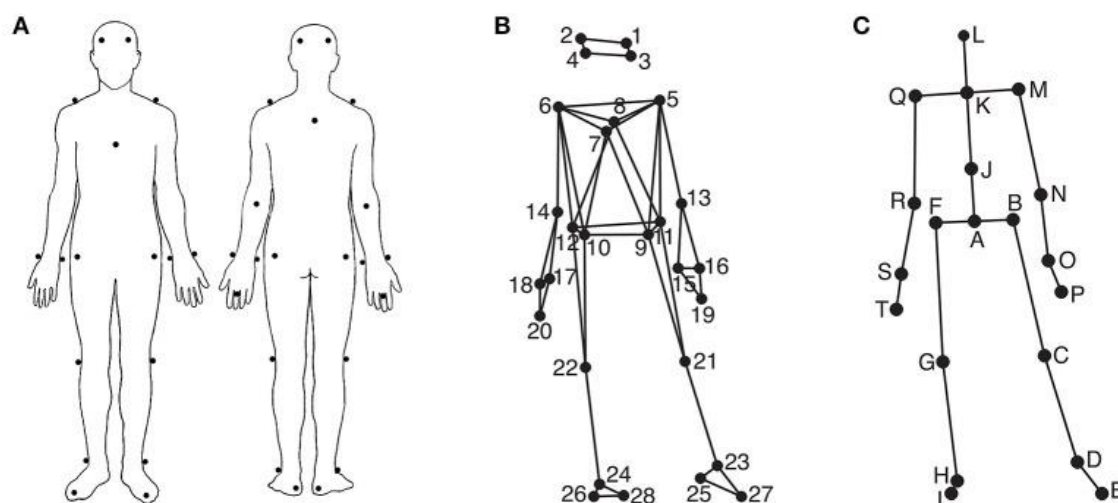


Figure 3. Marker and joint locations (Burger et al., 2014)

4.5 Musical feature extraction

The musical features pulse clarity, spectral flux, subband flux, and percussiveness were computed using MATLAB and MIRToolbox (version 1.6.1) (Lartillot et al., 2008), and the tempi of the stimuli were determined using perceptual data. Pulse clarity was estimated using the autocorrelation heuristic based on the onset detection curve which in turn was based on the amplitude envelope of the audio signal. For the extraction of spectral flux, a frame length of 50 ms was used with half-overlapping windows. To acquire subband flux values, the gammatone filterbank (Patterson et al., 1992) was used to divide the signal into ten frequency bands. The tempi of the musical stimuli were assessed by 5 independent raters. The raters were asked to tap along to the tempo of the piece using an online tap metronome, and to report the bpm given by the tap metronome, rounded to the nearest whole number. The interrater reliability was excellent, as demonstrated by a two-way random, average measures intraclass correlation based on absolute agreement, $ICC(2,5)=.99, p < .001$ (Shrout & Fleiss, 1979). To determine the tempo

for each stimulus, the median value of all the raters' tempo estimations was taken. The tempi of the musical stimuli can be found in Appendix 1.

4.6 Movement feature extraction

After the acquisition of motion capture data, the data were labelled to allow for further analysis. Because an optical motion capture system only records the light reflected by the markers, the system does not “know” which marker is which. Labelling refers to the process of giving the markers names and thereby telling the system which marker represents which body part. Also, lines connecting the markers, called bones, can be programmed and serve the function of making the figure more human-like. The digital representation of the markers is shown in Figure 3B, in which marker 1 represents the left back side of the head, marker 21 represents the left knee, etc.

In the current study, data were labelled in Qualisys Track Manager (version 2.12). The data were trimmed to start at the point when all of the markers become visible (after the participant had taken a few steps) and ending as soon as any of the foot markers disappeared from view when they got to the other side of the room (i.e. when they left the covered volume area as shown in Figure 2). After trimming, a walkway of approximately 4.5 metres per participant was usable for the analysis. Once the labelling was done, the mocap data were converted to tab-separated values (TSV) format. In the TSV format, the data contain information about the number of markers, the marker names, the position and time series data, etc. The position of each marker is shown in three columns, corresponding to the X, Y, and Z coordinates of that marker at each given frame. The rows represent the number of frames in each trial, meaning that each marker has three coordinates assigned to it per frame, which over time gives the full trajectory of each of the markers.

MoCapToolbox (version 1.5) (Burger & Toiviainen, 2013) was used in MATLAB to extract the movement features. First, the set of 28 markers was reduced to 20 joints (see Figure 3C) because some markers were redundant for the final analysis (e.g. information about rotation of the head was not needed). After this the gaps in the data (where markers went missing) were filled through linear interpolation (Burger & Toiviainen, 2013). Hereafter, the position and velocity data were calculated for each of the joints in three dimensions for each trial. The

position data was then used to calculate the mean distance between the two wrists in each trial. Finally, fluidity of movement in both hands and basic gait parameters (cadence, stride length, and walking speed) were calculated.

Cadence values were calculated by finding velocity peaks in the two heel markers. A peak in velocity occurs once per step, and this was used to determine the temporal locations of the steps. Signal Processing Toolbox (version 7.0) was used to find the peaks in the two signals. IOIs were then calculated by calculating the average time between footfalls for every trial. From these IOI values, the cadence values could be calculated. Stride length was calculated by using the peak locations, and calculating the Euclidian distance between the locations of the marker at the time of the peaks using the Statistics and Machine Learning Toolbox (version 10.0). Walking speed was derived from stride length and cycle time using the following equation:

$$\text{speed}(m/s) = \text{stride length}(m) / \text{cycle time}(s)$$

5 RESULTS

The movement feature values for each trial were averaged across participants, resulting in one value per movement feature per stimulus. These values were then imported into SPSS (version 23), where all subsequent analyses were conducted. The movement features were correlated with the musical features tempo (bpm), pulse clarity, mean spectral flux, spectral flux in subband 2, spectral flux in subband 8, and percussiveness. Due to the large amount of correlations, a Bonferroni correction for multiple comparisons was used.

Because the data was not normally distributed, a Spearman's rank correlation was used instead of a Pearson's correlation. The Spearman correlation showed that tempo was positively and significantly correlated with cadence and walking speed. Pulse clarity was significantly positively correlated with both cadence and walking speed, and negatively correlated with hand fluidity. Furthermore, a significant negative correlation was found between hand fluidity and subband flux in the 2nd subband, and mean spectral flux was correlated positively with cadence and walking speed, and negatively correlated with hand fluidity. All significant correlations had large effect sizes (i.e. a correlation coefficient higher than .5). No significant correlations were found for the musical features percussiveness and flux in subband 8, nor for the movement features stride length and hand distance. The full set of correlation coefficients with corrected p-values are displayed in Table 1.

	Tempo (bpm)	Pulse Clarity	Subband 2	Subband 8	Spectral Flux	Percussive- ness
Cadence (steps/min)	.539*	.718***	.423	.448	.550*	.484
Stride length (m)	.261	-.050	.067	.182	.131	.008
Walking speed	.607**	.665**	.442	.500	.554*	.457
Hand distance	.117	.366	.084	.247	.265	.077
Hand fluidity	-.460	-.610**	-.542*	-.466	-.543*	-.489

Table 1. Spearman's rank correlations between movement features and musical features. $N = 32$ for all correlations. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

To further investigate the effects of musical features on movement, a series of one-way analyses of variance (ANOVAs) were conducted between the movement features and four categorical variables. These categorical variables were: tempo group, timing (swung and straight timing), stimulus type (metronome stimulus or musical stimulus), and genre. In this context, the movement features were the dependent variables and the auditory features were the independent variables. To find the differences between specific groups, Tukey HSD post hoc tests were conducted.

A series of one-way ANOVAs were conducted to find differences in the means of movement features in the four tempo groups of the musical stimuli. A statistically significant difference in cadence values between tempo groups was found, $F(3, 28) = 4.55, p < .05$. A Tukey post hoc test revealed a significant difference in mean cadence values between the 80-85 bpm ($M 91.83, SD 6.64$) group and the 120-125 bpm group ($M 105.97, SD 10.32$) at a significance level of $p < .01$. A difference in walking speed was also found between tempo groups ($F(3,28) = 4.22, p < .05$). A Tukey test showed that walking speed was statistically significantly decreased in the 80-85 bpm tempo group ($M 1.71, SD 0.16$) compared to the 120-125 bpm tempo group ($M 1.97, SD 0.20, p < .05$) and the 140-145 bpm tempo group ($M 1.95, SD 0.18, p < .05$). A statistically significant difference in fluidity of movement was found between tempo groups, $F(3,28) = 4.39, p < .05$. Fluidity was significantly increased in the 80-85 bpm tempo group ($M .25, SD 0.02$) compared to the 120-125 bpm tempo group ($M 0.23, SD 0.01$) at a significance level of $p < .01$.

Another series of one-way ANOVAs was conducted on the four tempo groups of all the stimuli, including the metronome stimuli. In these analyses, more significant differences in movement features between groups were found compared to the previous ANOVAs with only musical stimuli. Statistically significant differences in cadence were found between tempo groups ($F(3,32) = 41.19, p < .001$). Cadence values in the first tempo group ($M 90.22, SD 4.92$) were significantly lower than the cadence values in tempo group 2 ($M 100.70, SD 4.22$), tempo group 3 ($M 108.53, SD 6.60$), and tempo group 4 ($M 114.68, SD 3.45$) at a significance level of $p < .001$. Furthermore, the cadence values in tempo group 2 were statistically significantly lower than in tempo group 3 ($p < .01$) and tempo group 4 ($p < .001$). There was no statistically significant difference in cadence between tempo group 3 and 4. Significant differences in walking speed were also found between the tempo groups in all the stimuli, $F(3,32) = 4.71, p < .01$. The walking speed in tempo group 1 ($M 1.73, SD 0.15$) was significantly slower than in

tempo group 3 (M 1.99, SD 0.19) and tempo group 4 (M 1.99, SD 0.20). Differences in fluidity of movement in the hands were also found ($F(3,32) = 5.53$, $p < .01$). The fluidity of movement was increased in tempo group 1 (M 0.25, SD 0.01) compared to tempo group 3 (M 0.23, SD 0.01, $p < .01$) and tempo group 4 (M 0.23, SD 0.02, $p < .05$).

Furthermore, a significant difference in hand distance was found between the two timing conditions swung timing (M 566.86, SD 8.72) and straight timing (M 575.87, SD 11.82), as determined by a one-way ANOVA ($F(1,30) = 5.71$, $p < .05$). A statistically significant difference between the music and metronome conditions (i.e. stimulus types) were found in terms of stride length ($F(1,34) = 7.59$, $p < .01$) and in terms of walking speed ($F(1,34) = 5.04$, $p < .05$). Stride length was increased in the metronome condition (M 1.18, SD .03) compared to the music condition (M 1.11, SD .05), and walking speed was increased in the metronome condition (M 2.09 SD .18) compared to the music condition (M 1.87, SD .19). There were no statistically significant differences between group means of any movement feature between the different genres.

To visualise the data, the mean cadence values of each trial were plotted against the tempo values of each stimulus. Figure 4 shows that in the trials, tempo and cadence generally did not match, with the exception of the stimuli between 100 and 105 bpm. If the cadence values matched the tempo values, the data points would have been on the identity line (the solid grey line), which depicts the $y=x$ line. When inserting a polynomial regression line (as seen in Figure 4), an inverted u-shape can be seen, meaning that the average cadence was decreased in the 140-145 bpm tempo group compared to the 120-125 tempo group.

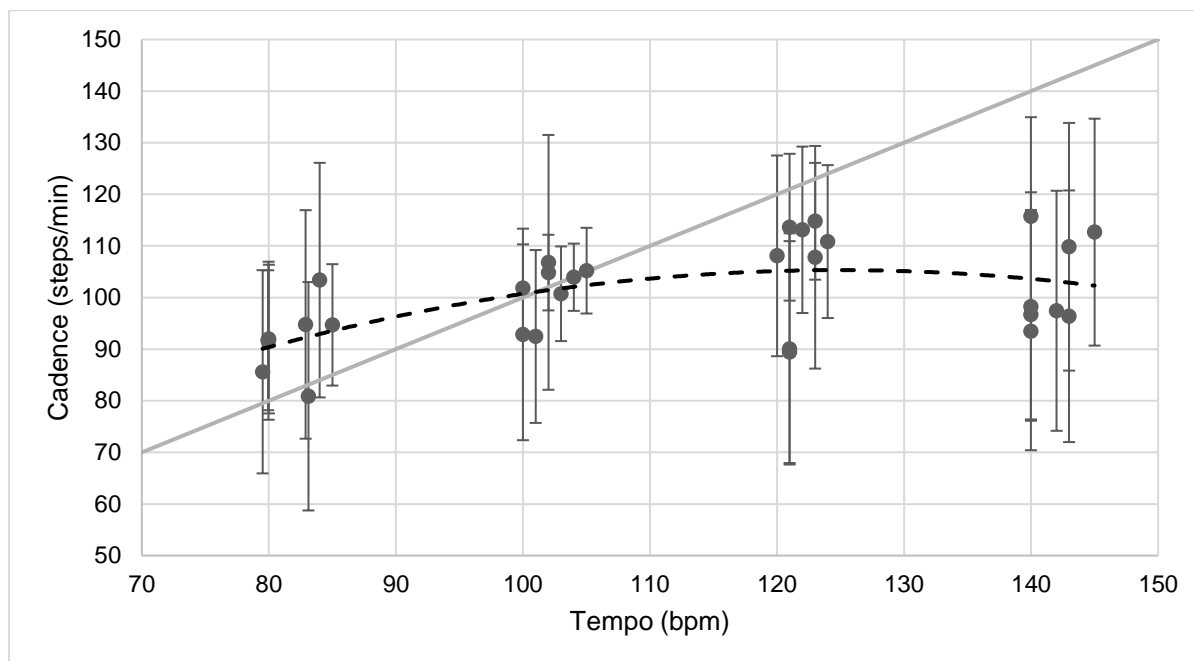


Figure 4. The tempo of the stimuli vs. the mean cadence. Error bars indicate *SD*. The solid grey line represents the identity line ($y = x$), in which the cadence values match the tempo values. The dashed line represents the polynomial regression line.

The low average cadence values and large standard deviations in the fastest tempo group are due to some participants' cadence being at double the beat period of the stimulus, that is, they were walking at half tempo. More specifically: in the fastest tempo group, there were 37 trials in which participants' cadence values (steps/min) equalled half the tempo in bpm (with a tolerance of $\pm 5\%$). In the slowest tempo group there were four trials in which the cadence value was half the tempo of the stimulus and one where the cadence equalled twice the tempo of the stimulus. In the second tempo group there were three trials in which a participant walked at half of the beat period and one trial in which the participant walked at double the beat period and in the third tempo group there were 16 cases of participants walking at half tempo. To account for the phenomenon of participants walking at half or double the beat period, all the cadence values that were half or double the value of the stimulus within a 5% tolerance were multiplied by two and divided by two, respectively. After this manipulation, there appears to be a near-linear relationship between cadence and tempo, with increased tempo corresponding to increased cadence values (see Figure 5).

When correlating the manipulated cadence values averaged over all participants with tempi of the musical stimuli, the resulting correlation coefficient between cadence and tempo is $\rho(32) = .97, p < .001$.

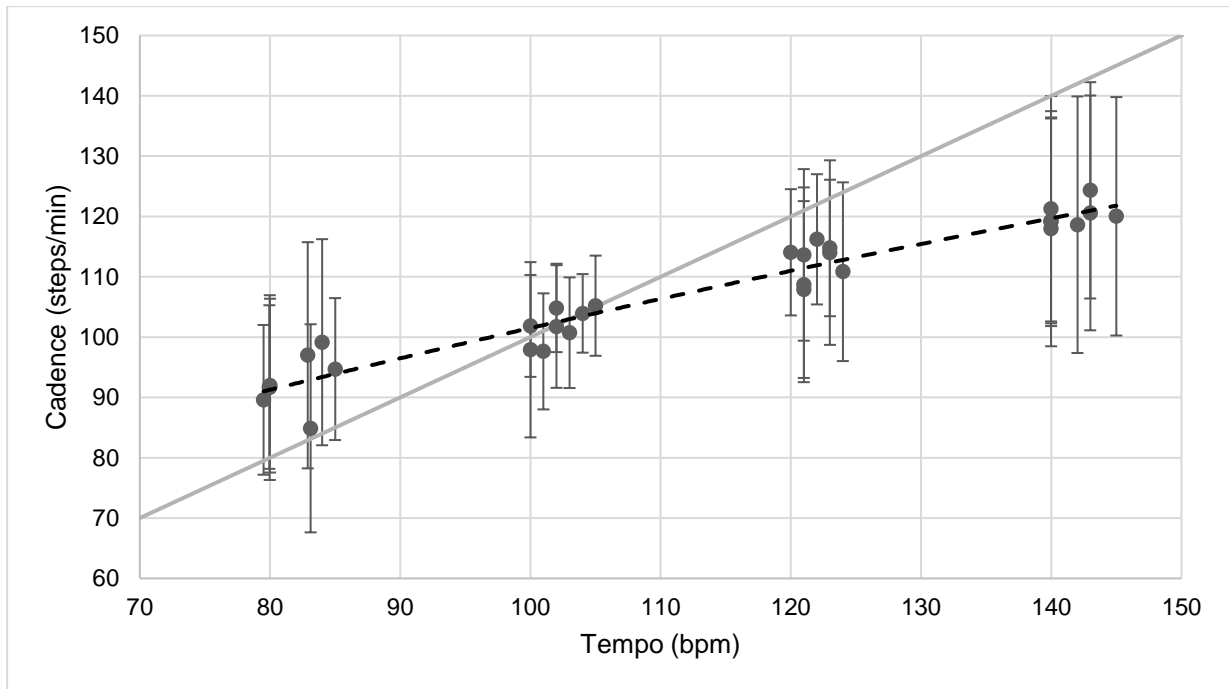


Figure 5. Average cadence values after adjusting for trials where cadence values were multiples of the beat period. Error bars indicate *SD*. The dashed line represents the polynomial regression line.

6 DISCUSSION

The current study aimed to measure the effects of rhythmic and spectro-timbral musical features on music-induced movement while walking. A motion capture study was conducted, whereby participants were asked to walk to musical and metronome stimuli, ranging from 80 bpm to 145 bpm.

Both cadence and walking speed correlated positively with tempo, pulse clarity, and spectral flux, suggesting that participants walked faster to music with a strong pulse and more spectral activity. Cadence and walking speed were also significantly decreased when walking to music between 80 and 85 bpm compared to faster tempi, suggesting that participants changed their cadence and by extension their walking speed in response differences in tempo in the music. Exact matching of the step period to the beat period generally did not take place, which may point to a certain range of preferred tempi that participants adjusted their cadence to. The preferred cadence appeared to be between 90 and 110 steps per minute (see Figure 4) instead of the expected 120 steps per minute (MacDougall & Moore, 2005), though this could have been influenced by a slightly slippery floor in the lab and the relatively short walkway. However, the positive significant correlation between cadence and tempo and the graphical visualisation of the data in Figure 4 do suggest an adjusting of the cadence towards the tempi of the stimuli, meaning that the music could have influenced cadence. These findings are in line with at least one previous study (Franek et al., 2014), confirming the hypothesis stated in chapter 0 and highlighting the importance of choosing stimuli that correspond to the preferred cadence of the participant.

Interestingly, the mean cadence was lower in the fastest (140-145 bpm) tempo group than in the 120-125 bpm tempo group (see Figure 4). This was due to a number of participants matching their cadence to double the beat period of the stimulus in the 140-145 bpm tempo group, resulting in cadence values of around 70 steps/minute. Because period-matching steps to a multiple of the tempo (i.e. half or double tempo) can still be seen as synchronisation, the cadence values that were multiples of the target tempo were adjusted towards that tempo. After adjusting the cadence values, a significant correlation was retained between cadence values and tempo of the stimuli, with a close to perfect correlation coefficient. Visually, the overall trend

of the data seems to take a more linear form with the adapted cadence values (see Figure 5), as opposed to the inverted u-shape with the original cadence values (see Figure 4). Therefore, with the adapted cadence values, the trend of increasing cadence with tempo appears to continue more consistently, and thus supports the expectation to see adjustment of the cadence towards the tempo, but not exact period-matching.

The type of stimulus used (i.e. music or metronome cue) also appeared to affect the basic gait parameters. Walking to metronome stimuli increased stride length and walking speed compared to musical stimuli. These results are not in line with previous findings in which an increase in stride length was found while walking to musical stimuli (Styns et al., 2007; Wittwer et al., 2013a). In contrast, Leman and colleagues (2013) found that music could evoke shorter strides than metronome beats could, but these excerpts were found to be relaxing in nature, and the opposite effect was found for stimuli that were activating in nature. The stimuli in this study were not rated on their emotional/motivational qualities, so these results cannot be compared. There were also increased differences in cadence and walking speed between tempo groups when metronome stimuli were used. This could indicate that participants were more likely to adapt their cadence to the metronome stimuli than to music. A possible explanation for this is that it could be easier or more natural to walk in time to a metronome beat because there are no ambiguities regarding tempo. The pulse and tempo in music can be ambiguous (McKinney & Moelants, 2006) and therefore it could be more likely to synchronise the footfalls to a subdivision of the beat or to walk off-beat.

Significant negative correlations were found between fluidity of movement in the hands and the musical features pulse clarity, low-frequency spectral flux, and mean spectral flux. Hand fluidity was also significantly increased in the slowest tempo group compared to the 120-125 bpm tempo group. This suggests that people move more smoothly to slower music with a less clear beat and less spectral activity than to faster music with a clear beat and a lot of spectral activity, especially in the lower frequencies. The timing of the music (i.e. swung or straight timing) affected the distance between the hands, with an increased hand distance in the straight timing condition, suggesting that music with straight timing evoked an increase in arm swing. Contrary to expectations, high-frequency spectral flux and percussiveness were not found to correlate with hand distance as was found in earlier research on dance-related movement

(Burger et al., 2013). This further emphasises the difficulties of translating musical connections to different types of movement.

The aim of the current study was to explore quasi-spontaneous movement to the stimuli, so the participants were not given direct instructions to synchronise. However, due to demand characteristics, participants may have synchronised even if this did not happen spontaneously. Since the trials took place in a motion capture lab, participants knew their movements were being recorded and this may have influenced their behaviour. Due to limited space in the lab and a relatively short walkway, only the initial steps (up to ten) could be recorded and any changes in cadence over time could not be assessed. Furthermore, because of the small sample size the results may not be representative of the population. Also, some musical stimuli changed character throughout the excerpt, for example: by the introduction of vocals or the start of a chorus after a verse. Therefore, the version of the song the participants heard depended on how long they chose to wait at the start of their stimulus before starting to walk. This could have been controlled for by letting participants only wait for a given amount of time (e.g. four bars) before walking.

Future research could consider collecting data in a more ecologically valid environment, such as a sports' track where participants walk with headphones on, or alternately to use a mobile phone application that can track participants' music listening behaviours in daily life. The participants' location could be tracked (e.g. through GPS data) providing information about walking speed and chosen route, and accelerometer data (e.g. the sensors present in smartphones) can give information about cadence. These settings would eliminate many problems present in a motion capture lab at the price of decreased accuracy of data and no possibilities to analyse ancillary movements such as arm swing.

Though it is difficult to draw any conclusions from the current study that are directly applicable to clinical practice, there are some preliminary recommendations that can be made concerning the use of gait cueing methods in clinical settings. First, it is important to choose stimuli with a tempo close to the preferred cadence of the patient, because when the tempo of a stimulus was too fast or too slow, participants generally do not match their cadence to the tempo. Thaut (2005) mentions that cueing stimuli should be adapted to patients' current *limit cycle* (i.e. the patient's preferred cadence), after which the stimulus tempi can gradually be increased or

decreased towards the patient's therapeutic goal (p. 143). Second, musical stimuli with a strong beat and high perceived activity, especially in the lower register (i.e. high pulse clarity and spectral flux) evoke the most "intense" movements, resulting in increased cadence and walking speed and less smoothness in the movements. Depending on the therapeutic goals of the patient, less fluid and faster movements could be advantageous. In contrast, music at slower tempi, with a less strong beat, and less spectral activity (especially in the lower frequencies) could result in slower, smoother movements. Third, music with straight timing could lead to more arm swing and more vigorous arm movements. Fourth, the current research suggests that cadence-to-tempo matching is most likely to take place with metronome stimuli, as opposed to musical stimuli.

The results of this study suggest that music and its rhythmic and spectro-timbral features can influence gait-related movements in young healthy adults. Furthermore, tempo, timing, and stimulus type also influenced the movements of the participants. To generalise these findings to other fields, most notably music therapy, more research is needed with different clinical populations, though some preliminary implications and recommendations for clinical practice could be formulated.

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Appendix 1 Song list

Title	Artist / Composer	Pulse clarity	Tempo (bpm)	Subband flux 2	Subband flux 8	Spectral flux	Percussiveness
Pas d'action: Andantino quasi moderato. From: Swan lake	Pyotr Ilyich Tchaikovsky	0,13	83	3.74	0.88	41.52	1.26
In the mood	Glenn Miller	0,42	84	22.1	2.54	69.47	3.38
Just a-sittin' and a-rockin'	Ella Fitzgerald / Duke Ellington & Billy Strayhorn	0,49	80	9.1	1.31	44.40	2.17
Brandenburg concert #2 in F major: Allegro Assai	Johann Sebastian Bach	0,56	83	3.26	1.19	41.81	2.21
Be your girl	Chieko Kabawe	0,56	80	22.65	5.84	86.55	2.89
You learn	Alanis Morissette	0,56	85	10.57	9.47	90.80	2.96
On a day like this	Elbow	0,57	80	20.15	14.53	118.06	2.67
Converting vegetarians	Infected Mushroom	0,67	80	11.67	4.46	66.61	6
Satin doll	Duke Ellington	0,30	100	5.22	0.81	32.69	2.1
Pueblo nuevo	Buena Vista Social Club	0,46	101	6.45	0.34	33.06	2.37
Russian march Op. 426	Johann Strauss	0,47	105	9.43	1.01	53.06	2.83
Sign of the cross	Iron Maiden	0,57	102	22.95	7.15	89.91	3.16
Superstition	Stevie Wonder	0,60	100	13.4	3.3	64.35	3.93
Pas de trois: Allegro semplice -Presto. From: Swan lake	Pyotr Ilyich Tchaikovsky	0,68	103	3.97	1.92	50.90	1.4
Clubbed to death	Rob D.	0,80	102	10.09	3.48	48.96	4.79
Stayin' alive	Bee Gees	0,82	104	16.78	4.76	60.75	4.24
Rex Tremendae Majestatis. From: Requiem in D minor	Wolfgang Amadeus Mozart	0,21	121	3.17	1.11	46.93	1.52
Bourée	Jethro Tull	0,37	121	3.02	0.07	15.50	2.33
Compulsion	Miles Davis	0,57	121	7.95	2.6	89.20	2.38
Whatever you want	Status Quo	0,72	122	23.59	6.1	123.18	3.7
Where does your mind go	Beardyman	0,74	124	15.31	4.74	120.65	2.37
King Cotton	Sousa	0,76	123	12.07	4.07	65.85	3.02

Martin Roachord's	Peatbog Faeries	0,73	123	18.41	9.95	130.77	2.68
Stupid girl	Garbage	0,78	120	8.06	3.34	53.60	3.76
What is this thing called love	Ella Fitzgerald / Cole Porter	0,21	142	6.52	2.7	72.53	2.98
Concerto for King Ferdinand IV of Naples, H 7/2 - 1. Vivace Assai	Joseph Haydn	0,40	140	2.53	0.98	37.26	1.94
Heeringas	Curly Strings	0,58	140	7.6	3.48	71.18	2.45
Longview	Green Day	0,59	143	16.78	4.96	84.61	2.78
Let's fall in love	Chris Botti / Arlen & Koehler	0,62	140	20.85	1.76	51.09	4.14
Call me	Blondie	0,75	143	9.69	8.41	83.63	4.04
The Irish rover	The Pogues	0,79	140	21.41	5.66	92.56	3.34
Vicious delicious	Infected Mushroom	0,93	145	10.61	3.39	63.15	5.85