UiO : University of Oslo

Agata Zelechowska

Irresistible Movement: The Role of Musical Sound, Individual Differences and Listening Context in Movement Responses to Music

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Department of Musicology
Faculty of Humanities

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Advisors:

Professor Alexander Refsum Jensenius, University of Oslo
Professor Bruno Laeng, University of Oslo
Associate Professor Jonna Katariina Vuoskoski, University of Oslo

Committee:

Professor Marc Leman, Ghent University
Dr Maria Witek, University of Birmingham
Professor Rolf Inge Godøy, Univerity of Oslo

Faculty of Humanities, University of Oslo

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Abstract

This dissertation examines the phenomenon of spontaneous movement responses to music. It attempts to grasp and illustrate the complexity of this behaviour by viewing it from different perspectives. Unlike most previous studies on music and body movement, this dissertation places the focus on barely visible manifestations of movement, such as those that may occur when listening to music while standing still. The point of departure is a reflection on movement responses to music and why such responses are considered universal among humans. This is followed by a discussion on the different approaches to studying how music 'inspires' movement, and an overview of the different factors that can potentially contribute to the emergence of movement responses to music. The first goal of the empirical research was to verify the common conception that 'music makes us move' and examine whether such movement responses can be involuntary. Three of the five included papers show that music can, indeed, make people move, even when they try to stand as still as possible. The second goal is to explore different factors that contribute to movement responses to music. Throughout the included papers, several topics are examined, including rhythmic complexity, tempo, music genres, individual differences and playback systems. The theoretical chapters show how these topics fit into three broader components of the music experience: music, listener and context. Overall, the results suggest that several factors seem to increase movement responses to music: the clear underlying pulse in the sound stimuli, the rhythmic complexity, a tempo of around 120 beats per minute, listening on headphones rather than speakers and high empathy of the listener. All in all, this dissertation contributes to bridging several gaps in the literature on music-related body movement. It also broadens the perspective on why, how and when music moves us.

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Agata Zelechowska
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List of Papers

Paper I

Jensenius, A. R., Zelechowska, A., & Gonzalez Sanchez, V. E. (2017). The musical influence on people's micromotion when standing still in groups. In *Proceedings of the 14th Sound and Music Computing Conference* (pp. 195-200). Aalto University.

Paper II

Gonzalez-Sanchez, V. E., Zelechowska, A., & Jensenius, A. R. (2018). Correspondences between music and involuntary human micromotion during standstill. *Frontiers in Psychology, 9*, 1382.

Paper III

Zelechowska, A., Gonzalez-Sanchez, V. E., Laeng, B. & Jensenius, A. R. (2020). Headphones or speakers? An exploratory study of their effects on spontaneous body movement to rhythmic music. *Frontiers in Psychology, 11*, 698.

Paper IV

Zelechowska, A., Gonzalez-Sanchez, V. E., Laeng, B., Vuoskoski, J. K. & Jensenius, A. R. (2020). Who moves to music? Empathic Concern predicts spontaneous movement responses to rhythm and music. *Music & Science, 3.*

Paper V

Zelechowska, A., Gonzalez-Sanchez, V. E. & Jensenius, A. R. (2020). Standstill to the 'beat': differences in involuntary movement responses to simple and complex rhythms. In *Proceedings of the 15th International Conference on Audio Mostly* (pp. 107-113).

Contents

Chapter 1

Introduction

1.1 Background

Music, and particularly musical rhythm, is linked with body movement in every known culture in the world. This universal phenomenon has recently gained traction as a research topic in musicology, music psychology and related disciplines. However, many questions remain unanswered about the relationship between music and the human body, and many common assumptions—which are primarily of an anecdotal nature—have not been backed up by sufficient scientific evidence. One of those assumptions is that music induces movement. Phrases such as ´music moves us' or 'music makes us move' are not only used in everyday language, but also often appear in research. But does music actually *move us*? Can we decide to move or *not* to move to music? What elements of music experience need to be present for us to be physically moved by music? These are some of the questions that I attempt to answer in this dissertation.

This dissertation is part of a larger research project titled 'MICRO - Human Bodily Micromotion in Music Perception and Interaction'. The project was started in 2017 by my main supervisor, Professor Alexander Refsum Jensenius. Together with postdoctoral researcher Victor Gonzalez Sanchez, we worked as a team on each of the research experiments and articles presented in this thesis. The core idea was to study small-scale body movements in the context of music perception. The main experimental paradigm employed in this project was developed back in 2012. It was based on a straightforward idea: to see whether people can stand still while listening to music, even when they try not to move at all. Or, more precisely—since we already know that people *cannot* stand completely still—to see whether they move more when exposed to music than in silence. Since then, five editions of the experiment have been run (in 2012, 2015, 2017, 2018 and 2019). Each time, different music stimuli were used and there were some variations in the procedure, but all the iterations have largely been based on the same idea and experimental paradigm.

When I joined the team, I proposed to add new research questions that stemmed from the main question (*Does music make us move?*), and developed an additional experimental paradigm to test them. I decided to focus on three components of embodied music experience: musical sound, listener and context. These topics are discussed in Chapter 3, and the corresponding research questions are introduced in Section 1.2.

The MICRO project, as can be derived from its full title, comprises two focal points: music *perception* and music *interaction*. As part of this project, *music interaction* was explored through numerous sonic performances and art installations. This was outside my main focus, so the articles that resulted from that work will not be discussed in detail in this thesis. However, since they were an important part of my work within the research project, and also fuelled ideas into its scientific part, they will be briefly summarised in Section 5.3.

1.2 Research Objective and Research Questions

The main research objective of this dissertation is to observe subtle body movements appearing spontaneously during music listening, to better understand the phenomenon of the human tendency to move to music.

The overarching research question is:

Does music make us move?

Multiple studies provide evidence for the tight coupling between music and body movement. The primary research interest of this dissertation is to scrutinize the common conception that ´music moves us’. Does music physically *move* us, as an external force moves an object? Does music *make* us move, as if manipulating our behaviour? Or do *we* move to music, perhaps because we want to or choose to do so? These questions relate to the issues of control, agency and volition, and the extent to which we have them while experiencing music. The experiments discussed in this dissertation only scratch the surface of the issue of volition in music-related movement. But hopefully, they can start a discussion that has so far been absent in the literature.

I believe that an exploration of the above question needs to involve a combination of theoretical and empirical work. While the papers included in the dissertation primarily present the empirical work, the background section focuses on the broader theoretical perspective. Here, a considerable amount of attention will be given to the following questions: *Why* do we spontaneously move to music? *Why* do we have an urge to move to music? Let us first dissect these two questions, and then dwell on the difference between them.

In this dissertation, I do not attempt to explore what *purposes* engaging in movement to music might have in general—for example, why people deliberately use music during sport activities, or spend Friday nights at dance clubs. Therefore, instead of asking *Why do we move to music?*, I place the focus on the *spontaneity* of and the *urge* for such movement. In this way, spontaneous movement to music is understood as a spontaneous response to music.

The term ‘spontaneous’ has several definitions and has taken on different meanings in the music and movement literature. In this thesis, it is used to denote a behaviour that happens without planning or external encouragement, as the result of an internal impulse. An alternative use of the term can be found in dance studies, in which ‘spontaneous movement’ is often used to describe any type of free movement without planned choreography. In such contexts, it is the performance, and not the emergence of movement, that is spontaneous. In this thesis, however, ‘spontaneous movement’ is understood as ‘spontaneously emerging movement’ (see ‘spontaneous movement’ in Section 1.5).

What is the difference between the above two questions (*Why* do we spontaneously move to music? and *Why* do we have an urge to move to music?), and why is it important? As compared to spontaneous movement, the *urge* to move can be felt, but not necessarily manifested as movement. This thesis targets both of these states, together with an area in between, which lies on the border of noticeably performed movement and withheld impulse. Therefore, the focus here is on small-scale movement, such as body sway or subtle head movements. Moreover, the subjective feeling of *moving* and *wanting to move* is discussed in comparison with the actual movement.

When it comes to the question *Does music make us move?*, I wonder whether it is even possible to provide a simple answer. Even if movement in response to music was hypothetically beyond our control, I oppose viewing it as a simple reflex; for instance, one that is similar to a pupil contracting in reaction to light. Therefore, I started asking *what* music can make us move? In *what* circumstances? *What* kind of person is likely to move? Thus, the three research questions emerged:

> **RQ1: What features of musical sound are needed to induce movement?**

When discussing my research in the early stages of the project, I was often asked the following question: how can you know that it is *music* that moves us and not just sound or any particular rhythm? This is precisely what I target in this research question. As such, musical sound is explored on several planes: by comparing silence and sound, rhythm and music, genres of music and particular music features. Multiple studies have looked at the role of various characteristics of musical sound in free, unchoreographed movement; for example, in synchronising with the beat or creating the urge to move. Here, the focus is on exploring the elements of musical sound which are needed to induce movement responses to music.

> **RQ2: What traits of listeners make them likely to spontaneously move to music?**

While movement to music seems universal among people, not everyone moves the same way. As we will consider more closely in Chapter 3, when people are asked to move freely to music, some quantitative and qualitative properties of their movement can be attributed to individual differences, such as psychological traits or experience with music. The question is: are some people more inclined to move in response to music? In this thesis, a large number of traits, habits, experiences and preferences are discussed and examined. Paper IV specifically deals with the topic of individual differences, but other papers also contain analyses that take into consideration individual characteristics of the participants.

> **RQ3: What context of music experience encourages body movement?**

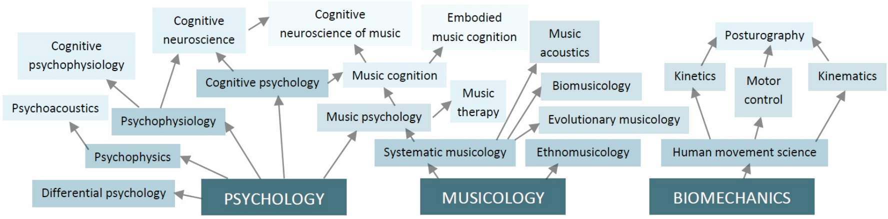

Figure 1.1: An overview of the relevant disciplines that provide background knowledge for this project.

The context of music experience can be understood in many ways. This thesis does not investigate all important contexts that shape the music experience, such as historical, sociological, cultural or political aspects. Compared to such large-scale contexts, my empirical approach is much narrower in scope, but as important: I focus on the the way sound is delivered to the perceiver. The empirical research presented in Paper III is a comparison between listening sessions that use headphones and speakers, and an examination of participants' body movements recorded during each session. While this paper involves just one particular component of the listening context, the study shows that headphones and speakers are technologies that affect various types of listening contexts, which are discussed in Chapter 3.

1.3 Theoretical and Empirical Framework

The framework for this research project encompasses theories and findings from a broad range of disciplines and fields (Figure 1.1). At large, it draws on knowledge from various fields of psychology, musicology and biomechanics. More specifically, it is rooted in the fields of cognitive psychology and systematic musicology. While Figure 1.1 attempts a categorisation of these and other relevant disciplines, it is difficult to draw clear borders between them. They are often categorised in different ways and within varying hierarchical structures. Ultimately, the academic disciplines tend to connect and merge with each other—this has been particularly true during the past several decades.

There are several theories of music cognition that provide the background to this thesis. The most important ones are theories of embodied music cognition (Leman, 2008) and motor-mimetic music cognition (Godøy, 2003), the theory of motor resonance and detectable agency in music (Launay, 2015) and the sensory–motor theory of rhythm and beat induction (Todd & Lee, 2015). Moreover, the project draws on various theories of the evolutionary origins of music and dance (e.g., Huron, 2001; Fitch, 2006; Launay et al., 2016).

1.4 Scope of this Thesis

The scope of this thesis is to study spontaneous body movement in response to music, and the urge for such movement. The main focus is on studying subtle movements that happen during music listening when people are not instructed to move. The methodological approach included motion capture, self-report measures, and an extensive theoretical investigation of empirical and theoretical literature from various disciplines (see Figure 1.1).

This thesis is not only highly interdisciplinary, but it also aims to provide a holistic approach for studying spontaneous movement to music. Instead of focusing on a narrow area within the studied phenomenon, the goal is to provide a broad perspective that takes into account various manifestations and explanations of spontaneous body movement to music. This is the main reason for including a relatively large number of research questions.

I realise that writing a dissertation is not only about choosing a particular focus, but also leaving out several others. There are many other research questions and topics that are relevant to the research area of this thesis. However, they are intentionally not discussed here. These are topics such as body movement (spontaneous or not) in a musical performance, musical gestures, choreographed dance, cultural aspects of embodied music experience, etc. Furthermore, the music material used in my own empirical research is not studied in depth in terms of its sociocultural, historical or theoretical background. The detailed biomechanics of human movement and posture, as well as a broader discussion on volition and control over bodily responses, are also not within the scope of this dissertation. Moreover, it is worth noting that even though synchronisation and entrainment to musical rhythm are some of the key concepts in discussions on spontaneous movement to music, the data analysis in the included research papers focuses primarily on the quantity of movement. The reasons for these limitations are considered further in Chapter 6.

Because of the interdisciplinary nature of this thesis, I encountered various challenges in bridging fields of research and the conventions established in each of them. The approach to studying body movement is different in psychology, musicology and biomechanics. The differences are evident in the various steps of creating knowledge: the collection and analysis of data (in the case of empirical research), and the ways of reflecting on existing knowledge on the research problem. This thesis does not aim to solve any of these issues, but points out some of them.

It should be clear from the beginning that each of the research papers included in this thesis is just a drop in the sea of possible approaches to my research questions. While the empirical papers usually investigate only one aspect of a given phenomenon (e.g., using headphones and speakers), the theoretical section of the dissertation aims to sketch a fuller picture (e.g., the context of music experience). Providing a broad and multifaceted background for the proposed research questions is, inevitably, at the sake of detail and depth of the discourse. Every presented theory has its own background and tradition, which could illuminate issues in the broader context, and every empirical research study is based on dozens of other studies, which are to a greater or lesser extent relevant to the subject. However, for the sake of brevity, these studies cannot all be presented here.

1.5 Core Terminology

Some of the terms and phrases commonly used throughout this thesis can be understood equivocally, and should, therefore, be clarified. Given the interdisciplinary nature of this thesis, the following definitions should be beneficial to readers coming from various backgrounds, who may be used to different theoretical frameworks within their disciplines.

Individual differences: A set of personal characteristics that vary between participants. This term is most often used in psychology to indicate the cognitive and emotional traits of an individual, such as personality traits or intelligence. In this thesis, however, a broader definition is used; it includes any personal characteristics that differentiate the participants according to preferences, habits, expertise, demographics, body morphology, etc. (see Section 3.2).

Listener/perceiver: These two terms are used synonymously in this thesis, with the aim of highlighting the multimodality of the music experience. In agreement with the theory of embodied music condition, this thesis opposes viewing music perception as based purely on *listening*, and it opposes the idea of *passive* music listening. Instead, it considers music experience multisensory and interactive, even in situations such as standing still and listening to music. For this reason, the term *perceiver* is often used instead of the more traditional *listener*. However, in some contexts and linguistic phrases, replacing the term *listener* with *perceiver* appears artificial or confusing, requires further clarifications, and is, therefore, avoided.

Micromotion: The smallest displacements of human body parts, typically at a speed of less than 10 mm/s, which are often difficult to notice with the naked eye. Micromotion can be voluntary or involuntary, conscious or unconscious. Involuntary micromotion appears when a person tries to remain as still as possible. Unconscious micromotion is that which a person is not aware of.

Motion capture: The technology enabling tracking and quantification of body movement. Unless otherwise specified, it refers to infrared, marker-based optical motion capture (see Section 4.3.2).

Movement/motion: In this thesis, the distinction between these two terms is not radical and their definitions are not substantially different. The choice of using one over the other depends on what appears more natural in a given context. The term *motion* is used mostly to describe quantified movement, and also in the context of motion capture technology. Movement is used in almost all other contexts. In some of the literature, the word *movement* carries a sense of intentionality, while *motion* suggests an objective state of the body or the result of applying an external force. Since this project deals with movement/motion that can be both intentional (voluntary) and unintentional (involuntary), and the difference between these two is not easily observable, such interpretations of these two terms are not implied here.

Movement/motor/physical response: The spontaneous emergence of movement (here in response to musical sound), which is one of many possible bodily responses to music.

Multimodality: The simultaneous engagement of several types of sensory experiences (e.g., auditory, visual, olfactory, tactile and kinaesthetic).

Music listening/music experience: Similarly to *listener* and *perceiver*, these terms are treated as synonymous and are used interchangeably, depending on the context and ease of use. The purpose is, again, to picture a multimodal, embodied experience of music.

Spontaneous movement: Spontaneously emerging movement (similar to *movement response*, *motor response*, *physical response*). When using *spontaneous movement* it is possible to discuss not only its emergence, but also its quantitative and qualitative properties.

Subtle body movement: While *micromotion* implies a minuscule scale of movement, typically smaller than 10 mm/s, *subtle* movement can occur at a larger scale. It still describes fine, delicate movements, but these are more likely to be noticed from a close distance. Subtle movement is a more liberal phrase that includes micromotion, but also more visible and deliberate movements, such as delicate head nodding, foot or finger tapping, etc. To illustrate, it is often possible to observe subtle movement among audience members during a classical music concert, but larger movement is typically not acceptable.

1.6 Thesis Outline

This thesis comprises two main parts. The first part provides a theoretical and empirical background to the project (Chapters 2 and 3), and also introduces, summarises and discusses the research contribution (Chapters 4, 5 and 6):

- Chapter 1 introduces the project and explains its core ideas, terms and research questions.
- Chapter 2 presents an overview of the theoretical and empirical studies that provide the background knowledge for investigating spontaneous movement responses to music.
- Chapter 3 provides the background for the three research questions and discusses how spontaneous movement is dependent on the listener, musical sound and context of the music experience.
- Chapter 4 describes the methodology used in all the included papers. It summarises the two main experimental paradigms, explains motion capture technology and self-report measures, describes the sound stimuli used in the experiments and discusses practical insights gained in the process of conducting the research.

- Chapter 5 summarises the research papers included in the second part of the dissertation. It also lists other authored publications that are not a part of this thesis, but were published parallel to this project.
- Chapter 6 discusses the work presented in this thesis. It summarises the results in relation to the research questions and provides a critical look at the limitations of this project. It also proposes ideas for future work on the subject.

The second part of the dissertation contains five research papers that have been published or submitted to scientific journals and conference proceedings over the course of this project (presented in a chronological order):

- Paper I presents the experimental paradigm of the Championship of Standstill and discusses an exploratory analysis of the data from the first experiment, which took place in 2012.
- Paper II discusses the Championship of Standstill further, displays data from the experiment that took place in 2017 and proposes new approaches to analysing the motion data and sound stimuli from the experiment.
- Paper III presents an experiment with two listening sessions: one with headphones and one with speakers. It critically compares these two types of playback systems and presents an analysis of the motion capture data collected during the two listening sessions.
- Paper IV explores the data set from the experiment of Paper III further, this time focusing on individual differences between participants. Data from the self-report measures used in the experiment are analysed in relation to the motion capture data.
- Paper V presents data from the Championship of Standstill that took place in 2019. This time the focus is on the rhythmic complexity of the stimuli, which comprise drum-based musical pieces in different tempi.

Supplementary material is available on the MICRO project website: https://www.uio.no/ritmo/english/projects/micro/.

Chapter 2

Body Movement

The connection between movement and music is so old and universal that they can be seen as an 'ancient marriage' (Sievers et al., 2013). Dance and other forms of movement to music are observed in all human societies (Kaeppler, 2000; Sievers et al., 2013; Laland et al., 2016), and in some cultures there is no clear distinction between music and dance (Stanford, 1966). Throughout human history, the kinetic power of music and its assistance in synchronising movement have been exploited in a variety of social activities, such as dance, sport, military drills, religious ceremonies and work in agriculture (McNeill, 1997).

Apart from their intentional use of music for movement activities, people often spontaneously start moving when they hear music, even if there is no obvious purpose for such behaviour. This can range from subtle movements (such as finger tapping or small head swaying), through more explicit movements (such as foot tapping, finger snapping, hand clapping, head bobbing or movements of the torso or arms), to dance and other types of large-scale movements that engage the whole body. There are certain situations where some kinds of movement to music are welcome (foot tapping to jazz music in a bar or dancing in a club) or unwelcome (finger snapping during a classical music concert or in a quiet library). Yet, regardless of social conventions, it sometimes seems that we just cannot help moving to music. Personally, I have often felt a sudden urge to move to music—which occasionally was difficult to control—in different ways, and I have observed similar patterns of behaviour in other people.

Everyday observations of the movement-inducing properties of music are reflected in the vocabulary used in research. When searching through the literature, I encountered expressions such as *'music moves us'* (Burger et al., 2012; Sievers et al., 2013; Swarbrick et al., 2019), *'music makes us move'* (Phillips-Silver & Trainor, 2007; Burger et al., 2012, 2013a,b), *'music impels us to move'* (Ross et al., 2016a), *'music compels us to move'* (Dalla Bella et al., 2013; Swarbrick et al., 2019), *'music enlivens our bodies'* (Iversen, 2016), *'proclivity to move with music'*, *'urge to move in response to music'* (Janata et al., 2012), *'propensity to move'* (Burger et al., 2013a), *'powerful immediate drive to dance'* and *'very strong, almost reflexive compulsion to move'* (Todd & Lee, 2015). One of my favourite quotes on this account is the following:

> *Whether it is through the subtle marking of time by means of minuscule head bobs or toe taps or through elaborate dance moves, the engagement of people's motor systems while listening to music is commonplace and seems to have an almost automatic, irresistible quality to it* (Janata et al., 2012).

While the assumptions of the *irresistible* and *almost automatic* qualities of movement to music correspond well to those made in daily life, they have received surprisingly little attention in empirical research. Most of the cited studies take the movement-inducing properties of music for granted, without referring to any empirical results. Furthermore, the empirical studies that give such results are few, and only one of them is specifically dedicated to spontaneous movement responses to music (see Section 2.3.3). Finally, none of these studies have investigated whether we can *resist* the urge to move to music—in other words, if music can move us even if we try not to move. This is one of the main goals of this dissertation.

In this chapter, I sketch the background of investigating movement as a spontaneous—and possibly irresistible—response to music. I start by reflecting on the different perspectives from which one can view movement as a response to music (Section 2.1). This is followed by an overview of explanations as to why people often respond to music with movement (Section 2.2). Then, I explain the concepts of synchronisation and entrainment to music (Section 2.3.1), which repeatedly appear in research on spontaneous movement, bodily responses and the urge to move to music. Furthermore, I discuss the concept of groove and the tendency to move (Section 2.3.2). In the last section of this chapter, I review the approach to measuring spontaneous movement to music in empirical studies, describing findings from a few experiments on movement as a response to music (Section 2.3.3).

2.1 Movement as a Response to Music

In this dissertation, movement is often described as a response to music. But what does it really mean to move *in response* to music? In behavioural sciences, and specifically in the field of cognitive psychology, a *response* is usually viewed as a behaviour that appears in the presence of a certain stimulus. This view pertains to the intended meaning of the *movement response to music* in this dissertation. Such an approach does not specify the reason for the response: it simply reports the observed behaviour.

At the same time, there are several other ways to understand what a *response* means, and occasionally these meanings are implicit when discussing human behaviour. In some studies, the term *response* is used to refer to an immediate, automatic reaction, which is possibly beyond our control, and similar to a *reflex*. For example, the pupil contracts in response to light. One cannot choose whether or not to contract the pupil—this is an automatic bodily process. However, in other contexts, a *response* can refer to a planned behaviour (e.g., a response to an opponent's move in a game), an emotion (e.g., a response to good news) or an opinion, whether expressed or kept to oneself (e.g., a response to someone's comments). Furthermore, a response can be described in several dimensions: it can be voluntary or involuntary, conscious or unconscious, immediate or delayed, expressed or suppressed, pleasant or unpleasant, mild or intense and so on.

What kind of response is movement to music? It could be viewed in many different ways:

- *Physiological*: the nervous system receives the stimuli and responds in a certain way.
- *Kinetic*: sound energy induces movement of the physical (human) body.
- *Culturally reinforced*: the listener has learned that moving to music is something that people do.
- *Expressive*: music induces a certain feeling that the person expresses with movement.
- *Communicative*: some information is transmitted through music, and the person responds to it in the form of body movement.
- *Desire*: movement is performed to satisfy a craving or to induce pleasure.
- *Signification*: through body movement, the listener forms their understanding of the rhythmic structure or a feeling conveyed by the music.
- *Artifact of brain functions*: music stimulates the brain in a way that triggers the execution of movement, similarly to a synaesthetic experience in which sound triggers, for instance, a perception of colour.

I would argue that movement responses to music can be all of these things, often in combination, and perhaps many more. At the same time, in this dissertation, I do not discuss which understanding of body movement as a response to music is most accurate, or how to use all of these perspectives to build a model of spontaneous movement to music. However, it is important to reflect on the different understandings of responses, because in the literature that has informed this thesis, some are more present than others. Movement to music is most often described as a bodily response, or as a psychological urge, drive or desire. Several studies also show how movement to music is a function of certain processes in the brain. These topics will be discussed in the following sections.

2.2 Why Do We Spontaneously Move to Music?

Body movement to music is actually a strange phenomenon. Is it not peculiar that we like to move our bodies to certain sounds? Many researchers agree that it is, and seek an explanation for this behaviour. Throughout the last decades, a vast number of studies have contributed little pieces that have helped to build a larger picture of why people often spontaneously move their bodies when listening to music.

2.2.1 Origins of Music and Dance

Back in the 19th century, Darwin (1871) hypothesised that music evolved as a communication system which preceded the emergence of language. He considered modern music a relic of a formal adaptation: the 'musical protolanguage', which has been eagerly discussed in research in the last two decades (Fitch, 2006; Mithen, 2006; Patel, 2010; Honing et al., 2015; Fitch, 2013). Some suggest that it was the other way round: music evolved as a byproduct of language evolution (Pinker, 1997). Either way, why do we *dance* to music? One hypothesis is that music started with percussive instruments (Kotz et al., 2018), which required making rhythmic movements to produce sound energy, thus creating a foundation for dance. However, simple forms of music, such as drumming on hollow logs, as well as dancing and singing, would leave no fossils. Thus, it is difficult to accurately reconstruct primitive music behaviours (Fitch, 2006). Nevertheless, cave paintings from as far back as 70,000 years ago are thought to represent human dance, indicating not only the early existence of such behaviour, but also its importance to people who lived at that time (Christensen et al., 2017).

Regardless of how dance emerged in the history of humanity, why was moving to music reinforced over the course of evolution? There are several theories of the potential adaptive value of dance. Some researchers speculate that dance was a way to display reproductive fitness in order to attract a sexual partner (Richter & Ostovar, 2016), which aligns with another hypothesis by Darwin that music could have played a role in sexual selection (Darwin, 1871). However, dance usually occurs in groups, so it is likely that it had a broader social role. For example, synchronising one's body movement with that of others could facilitate social bonding (McNeill, 1997; Huron, 2001; Phillips-Silver et al., 2010; Tarr et al., 2014; Launay et al., 2016; Richter & Ostovar, 2016), which is in agreement with some experimental research (Hove & Risen, 2009; Tarr et al., 2015, 2016; Woolhouse et al., 2016; Mogan et al., 2017). Furthermore, dancing may have served as a coalition signal and expression of within-group identity (Hagen & Bryant, 2003). Others speculate that it had no specific function, but rather evolved through the practice of imitating the body movements of others, which was useful for other purposes, such as cooperating on tasks that required synchronisation between people (Laland et al., 2016). Regardless of why we continued to dance throughout our evolution, this behaviour has been performed for thousands of years, which is perhaps why it feels so natural to move when we hear music.

2.2.2 Neurophysiological Basis of Movement to Music

Another group of studies focuses on the neural and physiological basis of motor responses to music. When performing music, one needs to both play and listen to the produced sound, constantly controlling and adjusting the actions according to the resultant sound. As such, performing music requires precise auditory–motor interactions, which can be seen as feedforward and feedback loops (Zatorre et al., 2007). Notably, the same network of sensory and motor representations is activated when a person is simply listening to music. A seminal study by Haueisen & Knösche (2001) showed that pianists who listen to recordings of pieces from their own repertoire spontaneously activate parts of the motor cortex that are responsible for finger movement.

Later studies have found that the activation of motor circuits when listening to music is not specific to people with musical training, but is rather a universal response to music (e.g., Grahn & Brett, 2007; Chen et al., 2008; Lima et al., 2016; Matthews et al., 2020). Furthermore, sound and movement are connected not only in the perception of music, but also in perception of other sounds. Many object-related actions can be recognised according to the sounds that they produce. Some studies on monkeys and humans have demonstrated the existence of groups of *audiovisual mirror neurons*, which are activated either when performing a specific action, when seeing it performed or when hearing the sound related to the action (Kohler et al., 2002; Keysers et al., 2003; Gazzola et al., 2006). In summary, the perception of sound and music shares a network of neuronal connections with the perception and production of movement.

The existence of a neurophysiological link between sound and movement was suggested before neuroimaging evidence emerged. Todd (1995, 1999) proposed that rhythm perception is mediated by both motor representations of the body and sensory representations of the auditory input, pointing out to the vestibular system in the inner ear, which plays a key role in deriving sensations of movement from sound (Todd & Cody, 2000). The vestibular system is involved in the maintenance of balance and perception of own body movement. It is also sensitive to stimulation by vibration and sound, particularly loud and low-frequency sounds. Indeed, music and auditory rhythms have been shown to influence human balance, which might be mediated by the functioning of the vestibular system (Forti et al., 2010; Ross et al., 2016b; Coste et al., 2018). Moreover, the vestibular system is connected to the limbic system, which means that its stimulation might also result in pleasure. This would explain why many people enjoy listening to loud music and music with a lot of bass; moreover, moving the head might further enhance the pleasurable sensations (Todd & Cody, 2000; Janata et al., 2012; Todd & Lee, 2015). Thus, not only can listening to music induce the sensation of body movement, but body movement might enhance the pleasure derived from listening to music.

Finally, some researchers view movement responses to music as a type of a physiological reflex. Several bodily responses, such as the aforementioned contraction of pupils in response to light, are governed by the peripheral nervous system. That is, they involve parts of the nervous system outside the brain and spinal cord, which form the central nervous system. Physiological responses to music may also be triggered through the peripheral nervous system (Russo & Liskovi, 2014). Such responses can include changes in respiration, perspiration, heart rate, blood pressure, skin and body temperature, muscular tension, gastric activity and biochemical processes in the body (Hodges, 2008, 2010; Russo & Liskovi, 2014). Hodges (2008, 2010) have proposed dividing bodily responses to music into *physiological* and *physical* responses, but have also noted that this division is somewhat arbitrary. Physiological responses are defined as ‘those bodily processes that happen internally' and physical responses are 'external events that we can observe' (Hodges, 2010, p.178). In Hodges (2008, p.121), this division is described in more detail:

- 'Physiological responses include internal bodily processes, such as heart rate. Although occasionally these internal processes are reflected in observable changes, for the most part detection requires some type of monitoring device.'
- 'Physical responses are external, readily observable, reflexive motor movements such as foot tapping. These responses occur naturally, without specific training.'

Physical responses can either be classified as only relating to body movements (Hodges, 2008), or as a compilation of 'muscular and motor responses' (changes in muscular tension), chills, facial gestures *and* body movements (Hodges, 2010). Thus, there is a sense of fluidity between physiological and physical responses reflected in the given definitions. For example, physiological responses can also *occasionally* be reflected as *observable changes*. Another issue that stands out in these definitions is that movement responses are seen as *reflexive*, which implies that they are *involuntary*. They are also described as *readily observable*, which seems to exclude minute movements that are difficult to notice without movement-sensing technology. I believe that these discrepancies in definitions, given by the same author, show that movement responses to music are indeed hard to grasp, and can be seen as both physiological and physical. Moreover, some physiological responses, such as changes in breathing or muscular activity, can induce or influence body movement in either a readily observable or a subtler way. In this dissertation, spontaneous movement responses to music are not classified as either physiological or physical, but studies on these types of bodily responses are considered particularly relevant. Thus, bodily responses will be discussed further in a number of contexts, along with studies on body movement to music.

2.3 Studies on Movement to Music

There has been a rapid growth in empirical studies on movement to music in the last few decades. Indeed, disciplines such as musicology, cognitive psychology and medicine (to name a few) stand to benefit from an understanding of how music can influence human movement. There are various approaches to such studies, depending on the type of movement (walking, running, finger tapping, head movement, body sway or dance), type of subjects (patients, healthy adults, musicians, children or animals), topics of focus (synchronisation between people, synchronisation to rhythm, characteristics of dance, health benefits or performance optimisation), type of music stimuli (metronome sounds, controlled rhythmic stimuli, music created for experimental purposes or real music), sensor technology used (optical motion capture, wearable sensors, force plates or observation without the use of technology) and other factors. In music research, there is a field of studies on body movement during music performance, interactions with music instruments, etc., but such studies are not discussed in this thesis. In the following sections, I focus on studies that could be most informative for understanding the phenomenon of spontaneous movement responses to music.

2.3.1 Synchronisation and Entrainment

The concepts of synchronisation and entrainment appear repeatedly in the literature about music and body movement, and seem crucial to understanding spontaneous movement responses to music. Movement appearing without instruction is usually rhythmic in nature and spontaneously synchronises to the beat of the music (Janata et al., 2012; Hurley et al., 2014; Kilchenmann & Senn, 2015), although the accuracy of synchronisation is higher among adults than small children (Zentner & Eerola, 2010). Thus, before moving on to the further parts of this dissertation, I suggest taking a closer look at these two phenomena.

Synchronisation, i.e., the alignment of at least two events in time (Keller, 2014), constitutes a substantial part of the human experience. To start with, biological processes in our bodies constantly synchronise to rhythms in the environment occurring at various time scales (Foster & Kreitzman, 2017). Moreover, many movements that we make are rhythmic in nature (for example, walking) and require precise synchronisation of several groups of muscles (Demos, 2014). We also have a tendency to spontaneously synchronise our movements with those of other people (Issartel et al., 2007; Knoblich et al., 2011; Demos et al., 2012; Codrons et al., 2014).

In the context of music, the human tendency to move is often discussed in parallel with synchronisation to rhythm. Rhythm plays a crucial role in inducing movement (Zentner & Eerola, 2010) and feelings of wanting to move (Madison et al., 2011; Senn et al., 2018). People also spontaneously synchronise their movements to music and auditory rhythms (Repp & Su, 2013; Van Dyck et al., 2015; Coste et al., 2018; Bouvet et al., 2020). In general, synchronisation—both to the movements of others and to the rhythm of music—gives a foundation to dance. Not every dance is rhythmic or involves synchronisation to events in the music or between dancers (e.g., this is true in butoh and some types of contemporary dance), although in most cultures dances are accompanied by rhythmic music, which affords temporal coordination of movement between people (Brown et al., 2006).

Entrainment is a concept similar to synchronisation, but its meaning is less clear than that of synchronisation. Depending on the discipline, the definition of entrainment tends to vary. In physics, it describes a spontaneous synchronisation of two or more independent rhythmic processes, such as of two pendulum clocks mounted next to each other—a classic example observed by the Dutch physicist Christiaan Huygens (Clayton et al., 2005). In the context of social sciences, entrainment occurs when individuals move together in time or share an affective state (Phillips-Silver, 2014). In neurobiology, entrainment is a process involving the adaptive synchrony of internal oscillations with an external event (Jones, 2008), and the coupling of oscillations in neural systems (Will & Berg, 2007).

Employing the concept of entrainment in music research was proposed by Clayton et al. (2005), understood as a phenomenon in which two or more independent rhythmic processes synchronise with each other (analogical to Huygens' pendulum clocks). At the same time, Clayton et al. (2005) suggested distinguishing several categories of entrainment, some of them diverging from the original concept. In *symmetrical* entrainment two processes align with each other, as in the case of the movements of two or more music performers. In *asymmetrical* entrainment the individual (or individuals) cannot influence the entraining rhythm, such as in the case of movement to recorded music. Finally, in *self-entrainment*, processes within an individual entrain to each other, as in the coordination of simultaneous motor activities in an individual performer. As such, the definitions of asymmetrical entrainment and self-entrainment are similar to the neurobiological understanding of entrainment.

The concept of entrainment has become popular in music research, and is used in a variety of contexts and with different meanings. For example, entrainment has been understood as a 'spatiotemporal coordination resulting from rhythmic responsiveness to a perceived rhythmic signal' (Phillips-Silver et al., 2010). It can also be understood as a 'process whereby an emotion is evoked by a piece of music because a powerful, external rhythm in the music influences some internal bodily rhythm of the listener (e.g., heart rate), such that the latter rhythm adjusts toward and eventually *locks in* to a common periodicity' (Juslin, 2013). Unfortunately, the term is not always defined clearly in the literature. Furthermore, new categories of entrainment have been proposed. For example, Phillips-Silver et al. (2010) distinguished between social entrainment (mutual or collective) and self-entrainment (defined as a rhythmic responsiveness to self-generated rhythmic signals), and Labbe & Grandjean (2014) differentiated motor entrainment (an inclination to move to the beat) from visceral entrainment (sensations of internal bodily entrainment to the beat). Evidently, despite attempts by music researchers to produce a unified theory of entrainment (Clayton et al., 2005; Phillips-Silver et al., 2010), the concept seems to have branched out in many directions.

What is the difference between entrainment and synchronisation in the context of body movement to music? This distinction is not clear in the literature, and the multiple definitions and subdivisions of entrainment do not help to clarify the issue. Some researchers suggest that entrainment provides the foundation for the synchronisation of movement to music by enabling a prediction of the following beat. When internal periodic processes of the human body entrain to external periodic stimuli (rhythmic music), the synchronisation of movement to the rhythmic stimuli becomes effortless and based on predictions of the following beat rather than being reactions to every beat separately (Large, 2000; Ellis, 2014; Moumdjian et al., 2018). In such an understanding, entrainment can happen regardless of whether or not it manifests in movement. It also suggests that spontaneous movement in response to music, if synchronised with the beat, indicates an ongoing entrainment process.

In this thesis, the term *synchronisation* is preferred over entrainment. This is because the main focus is on observable movement responses to music, rather than the processes that underlie such responses. It is highly likely, however, that many types of movements discussed in the following sections result from entrainment processes.

2.3.2 Groove and the Tendency to Move

Groove is a term that is often used in relation to concepts such as rhythm, pleasure and movement in music (Janata et al., 2012; Skaansar et al., 2019). What groove actually means, however, is not entirely clear. It can be understood as a type of repeating rhythmic pattern in music, a state of being in which creating music becomes effortless and euphoric or a pleasurable feeling of wanting to move (Schmidt Câmara & Danielsen, 2018). The last meaning is, naturally, the most relevant to this thesis.

For many years, music researchers focused primarily on studying a set of rhythmic properties that makes people perceive music as *groovy* (Madison et al., 2011). However, (Janata et al., 2012) proposed looking at groove as a psychological construct of a *pleasurable wanting to move to music*, or an *urge to move to music.* In order to systematise the concept of groove, they first tested how it is understood in the general population, rather than among music researchers. When asked to describe groove in their own words, participants referred to movement and rhythm (using words such as *move, dance, beat and rhythm*), and a sense of feeling or compulsion (*feel, make and want*), often in relation to their *bodies.* Furthermore, in response to a survey with 30 different statements on factors potentially contributing to the experience of groove, participants most strongly endorsed items relating to movement, positive emotions, immersion in music and the presence of prominent beats.

Based on these findings, (Janata et al., 2012) coined a definition of groove as ‘that aspect of music that induces a pleasant sense of wanting to move along with the music’. The concept of groove seems intuitive and is consistent between musician and nonmusician listeners (Madison, 2006; Madison et al., 2011; Janata et al., 2012; Witek et al., 2014), and to some extent, between cultures (Etani et al., 2018). Notably, previous definitions of groove used by researchers, although based on assumptions rather than systematic surveys, are fairly similar. For example, Madison (2006) and Madison et al. (2011) explain that groove ‘evokes the sensation of wanting to move some part of the body’.

Is groove just a feeling, or can it lead to actual body movement? Studies of groove usually include listening tasks with self-report measures, in which participants describe their responses to music stimuli. However, a few studies have shown that music perceived as groovy can indeed induce spontaneous movement, most commonly a rhythmic bobbing of the head (Janata et al., 2012; Kilchenmann & Senn, 2015; Hurley et al., 2014) (see Section 2.3.3). Apart from inducing movement, groove can also *influence* various bodily behaviours. For example, Ross et al. (2016b) found that groovy music influences postural sway, which becomes more regular and synchronises with periodic events in the music. The sensation of groove also modulates pupil dilation (Bowling et al., 2019; Skaansar et al., 2019). Neuroimaging studies have shown that regardless of actual movement, listening to groovy music engages motor and reward networks in the brain (Stupacher et al., 2013; Matthews et al., 2020).

Apart from insights into particular music features that underlie the feeling of groove (see Section 3.1.5), not much is known about other factors that give foundation to this phenomenon, such as individual differences or contexts of music experience. One could argue that the feeling of groove can depend on the individual listener's mental and physical responses, and general receptiveness to the (given) music (Levitin et al., 2018, p.65), or perhaps on their musical training (Janata et al., 2012, p.66). Even an extremely groovy song can fail to induce movement in some participants. Indeed, one study on groove that took into account participants' preferences and familiarity with the music stimuli showed that these factors can predict the groove experience better than music-related features can (Senn et al., 2018). Furthermore, Levitin et al. (2018) point out that participants sometimes report that although music stimuli give them the urge to move, they do not physically move, and vice versa. Does music need to pass a certain *threshold of grooviness* to induce physical movement? Are there other factors at play? Clearly, the relationship between the impulse to move and the execution of such an impulse is not well understood.

2.3.3 Dance and Spontaneous Movement

In the last two decades, using movement-sensing technologies in music research has grown in popularity. Using motion capture, video analysis and various types of sensors (see Section 4.3.2) enables researchers to look into details of how people move to music. Sometimes researchers focus on specific types of movement, such as drumming (Janata et al., 2012; Hurley et al., 2014) or playing air instruments (Godøy et al., 2006). Increasingly, the interest has been in free, improvised movement of the whole body, which is often referred to as *spontaneous* movement or *music-induced* movement. For example, researchers ask participants to *move freely to the music* (Van Dyck et al., 2013; Bamford et al., 2016), *dance freely* (Carlson et al., 2016), *move as freely as desired* (Carlson et al., 2018), *move as they feel comfortable* (Carlson et al., 2019), *respond freely to the music* (Bamford & Davidson, 2017), move *in any way that feels natural* (Luck et al., 2010; Burger et al., 2012, 2014; Burger & Toiviainen, 2018) or simply to *move with the music* (Eerola et al., 2006). Sometimes participants are asked to imagine a specific scenario; for example, being in a social setting such as a club or disco (Solberg & Jensenius, 2016; Carlson et al., 2016; Burger et al., 2017; Carlson et al., 2018). Occasionally, there is a specific instruction to synchronise with the beat (De Bruyn et al., 2009; Burger et al., 2017). The result of these various approaches is usually that participants dance or perform some isolated movements characteristic of dancing. It seems fair to call this *spontaneous* movement (understood as movement that is unconstrained and lacks imposed choreography) although this definition, as explained in Chapter

1, gives a different meaning to the word ‘spontaneous’ than that used in this thesis (understood as movement that *emerges* spontaneously). Indeed, the term *music-induced* movement seems somewhat misused, considering that all these studies specifically ask participants to move to music. The observed movement is certainly connected to music, but none of these studies shows whether the music *induces* movement.

The main interest in this thesis is in movement to music that happens without the instruction to move. Such movement typically occurs at a much smaller scale than dance does, and often engages particular body parts, such as the head, hands or toes. Surprisingly, these types of movement have attracted much less attention than dance has in music research. There are, however, a few studies that have tried to observe and measure a spontaneous emergence of movement, although this is usually a secondary topic in these studies. For example, Janata et al. (2012) asked participants to tap their hands on a drum pad to a range of rhythmic stimuli, as well as without stimuli, and recorded their body movements. The focus of this experiment was on the experience of groove (see Section 2.3.2) during sensorimotor behaviours. The authors were interested in two types of sensorimotor coupling with the music: *guided*, in which participants were asked to tap on a drum pad in different ways, and *spontaneous*, in which there was no instruction to move. The authors observed that in all conditions, regardless of the hand tapping, participants spontaneously moved other body parts, especially their heads and feet.

In a relatively similar experiment, Hurley et al. (2014) equipped participants with a drum pad and told them to tap to the music, if they wished. Apart from collecting tapping data, the researchers also recorded participants’ head movements, although there were no instructions to perform movements other than tapping. Unlike in Janata et al. (2012), participants in Hurley et al. (2014) had a motion capture marker placed on their foreheads. Thus, even though there was no instruction to move their heads, participants might have guessed that their head movement would be analysed. Not surprisingly, the authors observed spontaneous head movement during the tapping task, although its intensity varied between participants. However, this was only a secondary finding of the study, which primarily focused on musical qualities that create a feeling of groove (see Sections 2.3.2 and 3.1.5).

In another study on groove, Kilchenmann & Senn (2015) recorded the head movement of participants during a listening task that required them to rate music excerpts on several scales; participants did not know that their movement was being measured. As hypothesised, participants spontaneously moved their heads during the task. Finally, Swarbrick et al. (2019) measured head movement to live and recorded rock music in the realistic environment of a concert hall. Participants wore hats with attached markers and their head movement was recorded using a motion capture system. They were not encouraged to move in any particular way, and were asked to try to forget that they were wearing the caps and to enjoy the concert as they normally would. The authors observed head bobbing characteristic of the experience of rock music—this movement was faster to live than to recorded music. With this setup, however, it was probably clear to participants that their head movements would be analysed.

The study that is perhaps most relevant to the topic of this thesis examined spontaneous movement responses to music in infants (Zentner & Eerola, 2010). In this study, experimenters played various excerpts of music, rhythms and speech stimuli to children between 5–24 months old. They observed that infants spontaneously displayed rhythmic motion to music, regular rhythmic patterns and isochronous drumbeats (i.e., sequences of beats occurring at equal time intervals), but not to speech. Thus, a metrically regular structure seems crucial to induce movement in infants. This seminal study showed not only that rhythm plays an important role in inducing movement, but also that the tendency to move to music begins very early in human development.

Examining the body movement of infants differs substantially from examining the movement of adults. Technically, studying the motor behaviour of young children can be challenging, as they are still developing the sensorimotor skills necessary to stay upright and to coordinate the movement of different body parts. In the study by Zentner & Eerola (2010), infants sat on their parent's lap while listening to stimuli presented through speakers. The parents could not hear the music as they were wearing headphones, and they were instructed to avoid any movement except that which was necessary to prevent the infant from falling over. These constraints on the parents were important in order to eliminate the potential influence of their own responses to the music. Indeed, it is more difficult to study spontaneous movement responses to music in adults without somehow giving them the expectation that some kind of body movement should appear, either through the instructions of the experiment or the types of equipment used for collecting data (Janata et al., 2012; Hurley et al., 2014; Kilchenmann & Senn, 2015; Swarbrick et al., 2019). However, even with the explicit use of movement-recording technologies, there should be ways to further examine spontaneous movement responses to music in adults. One of the aims of this dissertation is to test several approaches to studying this topic.

As studies on spontaneous movement to music (without explicit instructions to move) are so scarce, I have decided to scrutinise studies on dance and free movement to music to find relevant background information for this thesis. Even if such studies examined body movement that was not entirely music-induced, they still highlight interesting characteristics of movement that relate to a range of variables. Similarly, studies on physiological responses to music show how human bodies respond to music, sometimes leading to explicit movement. Some of these studies show how different types of music induce different bodily responses, and that these responses vary between listeners. Such studies contribute to reflections on the role of musical sound, individual differences and the context of the music experience in spontaneous movement responses to music. These issues will be discussed in the next chapter.

Chapter 3

Music, Listener and Context

Claims such as ‘music moves us’ or ‘music elicits emotions’ are crude generalisations of complex phenomena. Some questions immediately follow: *What music*? *Who* moves? In *what situation*? It is difficult to fully grasp how people experience music (and move to it) without looking into the differences between various kinds of music, listeners and contexts. I believe that it is important to reflect on spontaneous body movement to music through (at least) these three lenses. While the role of different features of musical sound in body movement and bodily responses to music has been studied in considerable depth, only some studies have focused on the differences between individuals, and even fewer have discussed the potential impact of the specific contexts in which body movement to music is studied.

3.1 The Role of Musical Sound

The role of music in body movement, or in bodily responses to music, can be discussed from various perspectives. In studies on these subjects, music is often decomposed into particular structural or acoustic features of the sound signal, such as rhythmic complexity, tempo or spectral flux (see Section 3.1.5). Sometimes, differences between musical genres are discussed (Section 3.1.4). Less often, the impact of music is compared to the impact of noise (Section 3.1.2), and, rarely, the impact of silence (Section 3.1.1).

In the literature, there are various approaches to the design of music stimuli. Some researchers use highly controlled sound stimuli designed for the purpose of the experiment, while others prefer to use existing music. Occasionally, the impact of music is compared to that of a metronome track or other non-musical rhythmic stimulus (Section 3.1.3).

In daily life—and in various academic contexts—music is separated categorically from silence, noise and rhythmic structures. I like to see all of these as belonging to a continuum of various organisations of sound. On one side of the continuum, there is chaos or noise. On the other, there is pure structure, such as metronome sound. Different types of music fit somewhere in between these two extremes.

At the same time, music is not a purely acoustic stimulation (see Section 1.5, *Listener/Perceiver* and *Music Listening/Music Experience*). Instead, it can also engage different modalities, such as touch or vision (Godøy, 2003; Leman, 2008; Reybrouck et al., 2019). Moreover, it involves emotional responses, through memories and associations. For these reasons, it is difficult to isolate and compare various types of musical sound according to their impact on the listener.

The following sections summarise studies that shed some light on the impact of musical sound on body movement and bodily responses to music. Some of these studies are comparative (e.g., between genres), and some focus on particular aspects of sound (e.g., rhythmic structures or spectral properties). Insights from these studies informed the choices I made while designing and analysing the stimuli used in the experiments presented in this thesis, which are further explained in Sections 4.3.1 and 4.4.1.

3.1.1 Music and Silence

To understand how musical sound—or any other type of sound—impacts the human body, it is important to compare this condition to how the body behaves without any sound; that is, in silence. But what is *silence*? Is it possible to experience absolute silence?

The human body, unless dead, is never completely still: there are many ongoing physiological processes, such as cardiac and respiratory cycles, gastric motility, etc. Similarly, within the Earth's atmosphere, the sonic environment is never completely silent: there is always some sound that can be perceived by the human ear. Complete silence would be possible only if there was no medium—such as air or water—through which to transmit sound energy. The closest one can get to complete silence on Earth is within an anechoic chamber, which is a room that is designed to completely absorb all reflections of sound. But even therein, people can hear—more acutely than in normal conditions—the sounds of their own bodies, such as their heartbeats. Moreover, even with the tightest earplugs, not only are bodily functions audible, but some sounds from the environment are still transmitted through the vibrations of the cranial bones. In fact, environmental sounds play an important role in posture control (Gandemer et al., 2014), and sound deprivation (either in soundproof environments or by wearing ear-defenders) has been shown to disrupt balance (Kanegaonkar et al., 2012).

Apart from these physioacoustic factors, there are other potential problems that arise when comparing behaviour when listening to music and in silence. Perception of silence is based on the context and the interpretation of this experience. A great example is the famous piece by John Cage, *Tacet 4'33*, in which listeners experience 'silence' within the aesthetic frame of a music performance in a concert hall. By watching a performer on stage who does not produce any musical sound, the audience is invited to listen to the sounds of the concert hall, including the subtle sounds that other audience members make. The responses to this piece vary not only over the course of the piece, but also between listeners, depending on their expectations and interpretations.

In music research, Margulis (2007a,b, 2014) distinguishes between acoustic silence and perceived silence. In the case of silence fragments that happen inside music (i.e., pauses), the musical context in which they appear—for example, the preceding tonal sequences—affects how listeners perceive the silence. As such, pauses can be perceived as more or less tense or expressive, and longer or shorter, even if they are technically of the same duration and acoustic quality (Margulis, 2007b). They can also be described in different categories, e.g., silence as a boundary or as an interruption (Margulis, 2007a). Interestingly, neuroimaging studies reveal that the listener's attention shifts from the previous to the following phrase during pauses (Knösche et al., 2005). As such, pauses are coloured by the memory of what just happened and the anticipation of what comes next.

The context can also matter for the perception of silences that occur before and after a performance, and between pieces of music (e.g., between songs in a music album). For example, a silence may be perceived as unexpectedly long, which may raise the question: will the music come back? A silence can also seem too short, particularly in cases where the next song starts too soon, thereby not allowing for a proper closure of the previous song. Silence can be annoying if it interrupts a favourite song, or a relief if the music is perceived as unpleasant or tiring.

In studies on physiological responses to music, silence is often used to record baseline data. However, it has been shown that during silence periods between songs, cardiovascular activity comes even below baseline, and that silence can induce a relaxing effect more than slow or meditative music (Bernardi et al., 2005). In experiments, it is difficult to gauge whether participants imagine music during silence periods, and if they do, whether this imagined music is a 'replay' of what they just heard or a memory of some other previously experienced music.

To sum up, comparing behaviour to music and in silence is important for studying the impact of music on body movement and physiology, but some limitations should be considered. For example, laboratories may be soundproof, but they are typically not completely silent to start with. There may be sounds produced by electronic equipment in the space or a ventilation system, or faint sounds that pass through walls or windows. There may also be various types of body sounds in the space, coming from the bodies of the participants themselves, or the movement of other people (participants or experimenters).

It is also impossible to account for whether one imagines music, especially after a short music excerpt has just ended, and whether silence 'resets' the effects of the preceding music stimuli. It is difficult to say what happens in the transition periods between music and silence, and to determine the duration of these transitions. Moreover, participants may have certain ideas about the purpose of the silence segments in an experiment, which can influence their behaviour.

3.1.2 Music and Noise

Another approach to comparing bodily behaviour with and without music is to use noise as a contrast to music. It is, however, even more difficult to conceptualise noise than silence. Noise can be understood as meaningless sounds that we cannot recognise or classify; it can also be sounds that are unwanted, disturbing or unpleasant (Mazer, 2014). Music usually stands in contrast to noise as sound that is purposefully organised, meaningful and created to induce pleasure. Indeed, the distinction between music and noise is not objective; it depends on the perceiver and context (Mazer, 2014). As with the distinction between *acoustic silence* and *perceived silence* (Margulis, 2007b), there can be two levels of description for noise or any sound: the *physical-acoustic* description of the sound and the *subjective-psychological* reaction of the listener (Reybrouck et al., 2019).

Definitions of noise can vary depending on listeners' preferences and familiarity with some types of music; for example, one person may savour experimental electronic music or atonal orchestral music, and another might call these forms 'noise'. Noise can also be understood as unnecessary or disturbing loudness (Reybrouck et al., 2019). Some sounds (for example, rustling of dry leaves or the meowing of a cat) can seem interesting and pleasant at an optimal sound level, but when played too loud, they can be considered noise. On the other hand, many people enjoy listening to music very loudly (see *Loudness* in Section 3.1.5). It is also worth noting that just as with phrases of speech (Deutsch et al., 2011), non-musical sounds from the environment (for example, a car driving by) can become *musicalised* if repeated in sequences (Simchy-Gross & Margulis, 2018).

The impact of noise on the human body is not fully understood; it is also hard to summarise the relevant literature. Exposure to noise with high sound pressure levels and for a long time can lead not only to hearing loss, but also to vibroacoustic disease, which includes changes in the nervous system, heart functioning, blood vessels and respiratory tissues (Castelo Branco & Alves-Pereira, 2004). The sound frequency of the noise also plays an important role. Research on the impact of infrasound (i.e., sound frequencies below the human hearing threshold) and low-frequency sound on human health shows that exposure to such sound in everyday environments leads not only to annoyance, but also to sleep-related problems, concentration difficulties and headaches (Baliatsas et al., 2016). More immediate effects include changes in cardiac and respiratory rhythms and other disturbances of the central nervous system (Broner, 1978).

On the other hand, in experimental conditions and at an optimal sound level, auditory white noise has also been shown to improve postural stability (Ross & Balasubramaniam, 2015). Unfortunately, research on bodily responses to noise typically does not compare them to bodily responses to music.

3.1.3 Music and Rhythm

In studies on body movement, the impact of music is sometimes compared to that of 'non-musical' auditory rhythms. Typically, metronome tracks are used for this purpose, based either on the sound of an acoustic instrument (often a woodblock-like sound) or on synthetic clicks. Thus, it is possible to eliminate the potential impact of other music features, such as melodic fluctuations, harmonic and timbral complexity, changes in dynamics, as well as emotional and semantic qualities of the music. However, considering that sounds that appear in sequences are often perceived as musical (Simchy-Gross & Margulis, 2018), assumptions that rhythmic sounds can be deprived of musical properties are debatable.

Rhythmic cues are sometimes used in the rehabilitation of clinical patients who have impaired motor control (e.g., due to a stroke or Parkinson's or Huntington's disease). Using rhythmic stimuli engages brain structures within key motor networks (see Section 2.2.2) that are often impaired in such diseases (Nombela et al., 2013).

Studies on music and motor rehabilitation typically use *either* metronome tracks *or* music as auditory cues, and occasionally the metronome sound is embedded in the music stimuli (Nombela et al., 2013; Ashoori et al., 2015). One study showed that Huntington's disease patients benefited less from music cues than metronome sound, which enabled them to walk faster (Thaut et al., 1999). Another study that used music to aid walking, but in a group of healthy older adults, showed that music cues (but not a metronome) increased their stride length and walking speed. The metronome track also evoked increases in these measures compared to when there was no stimulation, but the results did not reach significance (Wittwer et al., 2013).

Several studies have compared the impact of these two types of cues on body movement in young, healthy populations. For example, Styns et al. (2007) report that young adults walk faster to music than to metronome cues. In contrast, Leow et al. (2014) found that participants could synchronise their walking better to metronome cues than to music. However, the same study compared walking to low- and high-groove music, and found that high-groove music elicited better synchronisation and faster walking speeds. Furthermore, low-groove music even had a detrimental effect on walking: the steps were slower, shorter and wider compared to uncued walking, and synchronisation was poorer than in the case of high-groove music and metronome cues. It seems that the benefit of using rhythmic cues is moderated not only by rhythmic complexity, but also by individual differences in beat perception and familiarity with the music stimuli (Leow et al., 2014, 2015). Both familiarity with the music and better rhythm perception can increase the ease of extracting the beat, thus leading to better synchronisation of movement.

Acoustic stimuli are often used to optimise movement in sports (Karageorghis & Priest, 2012b,a). Several studies compare the impacts of various types of music and metronome cues. For example, Hayakawa et al. (2000) showed that both aerobics dance music (used synchronously, i.e., matching the movement tempo) and Japanese folk music (used asynchronously) lessened people's feelings of tiredness during aerobic exercise when compared to using a metronome track, which had the opposite effect. Furthermore, among these three auditory conditions, only dance music increased their feelings of vigour.

In a similar study, (Bood et al., 2013) compared the effect of the presence or absence of acoustic stimuli on running using a metronome and motivational music stimuli that synchronised with running tempo. Participants were able to run for longer before feeling exhausted when they had an acoustic stimulus than without it. Surprisingly, there was no significant difference between a metronome track and motivational music on participants' exhaustion.

Crust & Clough (2006) compared how no music, rhythm and motivational music impact performance in a weight-holding task. Participants held the weight suspended for significantly longer with motivational music than without it, and even listening to a rhythm improved their performance compared to the no music condition. However, it is not clear whether the rhythm condition in this study was a metronome track or some other type of auditory stimulus. Additionally, this study found a relationship between responses to the motivational music and personality: participants scoring high on liveliness—a personality factor connected to enthusiasm and spontaneity of behaviour—were more responsive to the motivational music (Crust & Clough, 2006).

The above studies show the impact of music on *performance*, but not on the *emergence* of a response to music. There is no evidence for the advantage of music over simple rhythmic stimuli in encouraging movement. On the contrary, Zentner & Eerola (2010) showed that rhythm is just as effective as music in eliciting spontaneous movement in infants (and both are more effective than speech). It is noteworthy that in this study, instead of a typical metronome track with a click or beep sound, the authors used isochronous drumbeats, which are perceptually more similar to music. Still, there are no studies on adults spontaneously moving to music as compared to simpler rhythmic stimuli.

3.1.4 Music Genres

Apart from studying the impact of music on human movement and bodily responses compared to the impacts of silence, noise or rhythms, it is also intuitive to compare different types of music. A popular way of categorising music is by *genre*.

Some music genres are more strongly associated with movement than others. Think about, for example, samba compared to opera. There are also some genres that are associated with specific types of body movements, such as foot tapping to jazz, hip movements to salsa, head banging to rock music, and so on. Luck et al. (2010) compared how different music genres inspire different types of body movement in a task where participants moved freely to music. They played selected excerpts from jazz, Latin, techno, funk, and rock for the participants, and found that some genres drove movement components more than others. As expected, they observed head banging movements to rock (particularly in participants scoring high in Extraversion); there was also less movement across the recording space for this genre. Extraverted participants also moved their heads vigorously to techno, which, generally, inspired all participants to move their limbs. Latin music made participants move around the room while keeping their heads relatively still. The latter was also observed in response to jazz, although movement patterns to jazz and funk were less clear (Luck et al., 2010). The authors admitted that their choice of music genres was dictated by their allegedly high movement-inducing properties. All genres had a strong, periodic rhythmic layer.

In their study on music features that contribute to the feeling of groove, Madison et al. (2011) used examples from five distinct traditional music genres: Greek, Indian, jazz, samba, and West African. Their choice was motivated by the diversity of these genres and the assumption that these music genres had little influence on mainstream Western music. Participants listened to the samples and rated their feeling of groove, i.e., 'to what extent they evoke the sensation of wanting to move some part of the body'. The researchers found that West

African, samba and jazz were the most successful in evoking feelings of groove, followed by Greek and Indian music. Within genres, participants' ratings were most consistent for jazz, and least consistent for samba and Greek music. The authors advised against extrapolating their results to the genres as a whole, as their process of choosing music samples was 'not systematic'.

Not surprisingly, as seen in Luck et al. (2010) and other studies on the free movement to music, it is typical to use music genres that are considered groovy or that are highly associated with dancing. One genre that is used particularly often in studies is electronic dance music (EDM) (Moelants, 2003; Zeiner-Henriksen, 2010; Van Dyck et al., 2013; Solberg & Jensenius, 2016; Ellamil et al., 2016; Burger et al., 2017; Solberg & Jensenius, 2017). There are many factors that support using stimuli from this genre to study movement to music. First, the music is specifically designed for dancing and is often composed with the goal of making it difficult to resist movement. It has some movement-inducing properties, such as a strong low-frequency beat (see Section 3.1.5). Moreover, EDM is highly popular in Western societies across various social circles (unlike, for example, jazz), and its elements are often present in mainstream pop music. Indeed, when compared to genres such as funk, jazz or Latin music, EDM is shown to induce more movement in free-dancing participants (Burger & Toiviainen, 2018). However, it is important to note that EDM encompasses a broad range of sub-genres, and not all of them might be equally movement-inducing. It is also important to take into consideration cultural aspects as well as personal music preferences (Wesolowski & Hofmann, 2016).

3.1.5 Music Features

Apart from genres, there are several different music features that have been scrutinised in studies on body movement to music, such as syncopation, tempo and spectral properties. In studies on music-induced movement and free dance, the focus is often on particular music features that elicit wanting to move (Madison et al., 2011; Davies et al., 2013) or on the interaction between music and movement features (Burger et al., 2012, 2013b, 2014, 2017; Burger & Toiviainen, 2018; Witek et al., 2017). Although not discussed widely in the literature, it is worth studying not only the effect of individual music features on body movement to music, but also the interactions between these features (Burger et al., 2017). Moreover, dynamic changes occurring within a music piece, such as in tempo or dynamics, can also influence body movement (Burger & Toiviainen, 2018; Bharucha et al., 2006, p.161).

In the following section, we look at music features that are most relevant to the main topic of this thesis, i.e., spontaneous movement responses to music. While I mainly discuss features that relate to the properties of the sound signal within the music pieces, I also include loudness as a music feature, although it could arguably be considered a feature of the music context (see Section 3.3).

Tempo

Tempo is the rate at which repeating events occur. In the case of rhythmic music, tempo is dependent on the time intervals between the beats, often described as beats per minute (BPM). Music tempi can range from about 50 to 200 BPM. Most people indicate a preference for music at a tempo that is between 120 and 125 BPM (Moelants, 2002), i.e., about two beats per second. However, tempo preference depends on the purpose of the music: relaxing music typically has a slower tempo than dance music. For dancing, on average, people prefer a tempo of around 125–130 BPM (Moelants, 2008). However, the tempo varies greatly between different types of dance music, depending on what kind of movements they are expected to elicit (Moelants, 2003). In the case of walking to music, Styns et al. (2007) found that people have a preference for a tempo of 110–120 BPM.

Most studies on free, dance-like body movement to music use stimuli with tempi common to dance music. To compare how people move at different tempi, Burger et al. (2017) used songs with 105, 115 and 130 BPM. They observed an interesting relationship between tempo and the low-frequency content of music: participants were worse at synchronising their movement to music with faster tempi when the content of low-frequency sound was stronger. When it was weaker, however, participants synchronised best to music with 115 BPM. In their earlier study, the tempi of music stimuli failed to have an effect on movement (Burger et al., 2013b).

Studies on movement features that contribute to the feeling of groove found mixed results for the effect of tempo. A study by Etani et al. (2018) suggests that the optimal tempo for groove is within the range of 100 to 120 BPM, but Madison et al. (2011) found that the tempo plays a minor role in the feeling of groove compared to other music features across music genres. However, in an earlier study, Madison (2003) found that groove ratings decreased with a decrease in tempo for the same music record. This is similar to the findings of Janata et al. (2012), who observed higher groove ratings to music that has faster tempi. Furthermore, unlike the other studies, Etani et al. (2018) used drum samples rather than real music, so it is possible that the effect of tempo is more pronounced if other music features are reduced.

The preferred tempo for movement can also vary between people. Dahl et al. (2014) found that the preferred tempo for dance depends on the shape of the person's body, and particularly, their height and leg length. The body-dependent tempo preferences for movement can be explained using the resonance theory of tempo perception, in which the body is seen as an oscillator that has a fixed resonance frequency, and which can be moved by an external force, i.e., the beat of the music (van Noorden & Moelants, 1999; Moelants, 2003).

Rhythm

A large portion of the research on music features that are movement-inducing and contribute to the feeling of groove is focused on rhythmic qualities. Madison et al. (2011) points out that unlike a metronome track, music has a metrical structure (i.e., hierarchical divisions of shorter and longer intervals), which enables movement synchronisation at different levels. By adding temporal information, metrical structure aids both temporal precision of movement and the production of movement patterns over a longer period of time.

In the search for an optimal rhythmic structure for movement, researchers often focus on two particular rhythmic features: microtiming and syncopation. Microtiming can be understood as systematic or non-systematic deviations from the metrical grid—for example, the beat always comes a bit early or late (systematic), or varies between early, late and on time (non-systematic). While systematic microtiming is usually a deliberate aesthetic manipulation, non-systematic microtiming results from the limits of human perception and motor control (Madison et al., 2011) and is natural to music that is not produced using computer programs.

There is a lack of consensus on whether microtiming influences the movement-inducing properties of music: it can either increase (Keil, 1995; Iyer, 2002) or decrease (Davies et al., 2013; Frühauf et al., 2013) the feeling of groove, or not play a significant role at all (Madison et al., 2011). Perhaps it depends on the scale and type of microtiming, and the musical background of the listeners (Senn et al., 2016, 2017, 2018). Apart from studies based on ratings of groove, there is some evidence that microtiming can stimulate actual movement (Kilchenmann & Senn, 2015), but with moderate effect, and only in listeners with musical expertise. Moreover, microtiming can influence how people synchronise their movement with music (Danielsen et al., 2015).

Syncopation, in turn, can be understood as rhythmic complexity achieved by shifting rhythmic emphasis from strong to weak beats in a musical metre, thus violating listener's metric expectations (Witek et al., 2014, 2017). It seems that there is a U-shaped relationship between syncopation and the pleasant feeling of groove (Witek et al., 2014; Sioros et al., 2014). However, in a study on actual body movement, Witek et al. (2017) found that while high levels of syncopation discouraged participants from moving, there was no difference between movement in low and medium syncopation. On the other hand, these studies did not use real music, but custom made rhythmic patterns.

It should be noted that not all music is based on clear rhythmic structures. For example, Gregorian chants do not have a beat or regular metric accents, and some types of folk music have asymmetrical beat structures (e.g., Norwegian telespringar is based on a *long-medium-short* duration pattern). Using such types of music to induce body movement has not been popular in embodied music cognition studies.

Spectral Properties

Recent research suggests that the spectral properties of music, particularly the content of low frequencies, influence body movement and the feeling of groove. Hove et al. (2019) analysed the evolution of the music features of popular music throughout the years (1955–2016) and noted an increase in the use of low frequencies, particularly in the frequency band between 0–100 Hz. While this may result from technological advancements, the authors attribute this change over time to the goal of increasing listener's engagement with the music and inducing body movement.

Empirical research shows that the content of low-frequency sound has a large impact on how people move to music. For example, Van Dyck et al. (2013) observed that the bass drum is particularly important for inducing movement. In their study, participants moved their hips and heads more actively when there was an increase in the sound pressure level of the bass drum. Enhanced bass drum sound also facilitated the synchronisation of movement to various tempi. Furthermore, Burger et al. (2017) showed that large amounts of low-frequency components in music influenced how participants moved in a free dance task. Intensified bass helped the participants to synchronise their movement with the beat at slow tempi. In another study, Stupacher et al. (2016) manipulated the attack time (short vs. long) and content of low frequencies (low vs. high) in the bass drum in music. They found that lower bass drum frequencies increased groove ratings and influenced tapping performance, i.e., participants tapped harder and at a more constant rate. Similarly, Varlet et al. (2018) found that participant's spontaneous synchronisation of movement (swinging a pendulum) to a metronome track was more stable, and the movement had a bigger amplitude, when the metronome sound was low-pitched (100 Hz) rather than high-pitched (1,600 Hz). Low-frequency sound may stimulate and alter body movement more due to its effect on the vestibular system. This system is particularly sensitive to low-frequency sound, and, at the same time, it is strongly connected to the perception of rhythm and sensations of body movement (Todd et al., 2008; Todd, 2015; Todd & Lee, 2015, see Section 2.2.2).

Loudness

As mentioned in Section 3.1.2, Reybrouck et al. (2019) distinguish between two ways of describing sound: the physical-acoustic properties of the sound, and the subjective-psychological reactions of listeners. The impact of these two, in the context of bodily responses to music, is sometimes hard to distinguish. A good example is that of sound pressure level versus loudness. The first is a measurement of the physical signal, while the latter is subjective and can vary not only between listeners, but also depending on the context. Studies on acoustics typically focus on the sound pressure level, while music perception studies more commonly focus on loudness.

Dancing rarely happens to quiet music. Dance music today usually depends on amplification, but some ancient forms of dancing employed loud drums (Todd & Lee, 2015). People seem to enjoy loud music, not only for dancing, but also at live concerts, fitness centres and bars, and when listening on personal audio systems (Welch & Fremaux, 2017a,b). Indeed, the overall loudness of popular music seems to have increased over the last few decades (Serrà et al., 2012; Hove et al., 2019). But why?

Loud music, especially if rich in low frequencies, can induce vibrotactile and vestibular sensations, including feelings of self-motion (Todd & Cody, 2000; Todd & Lee, 2015; Reybrouck et al., 2019); it can also increase arousal (Welch & Fremaux, 2017b). Apart from the physiological reasons, enjoyment of loudness may be dependent on acculturation and even personality (Welch & Fremaux, 2017a). Unfortunately, there are no studies that directly compare the impact of loud versus quiet music on spontaneous body movement to music. One study on groove showed that in a music listening task, loudness did not contribute to the feeling of groove (Stupacher et al., 2016).

3.2 The Role of Individual Differences

Individual differences is a phrase used to describe the various characteristics based on which people differ from each other. In differential psychology studies, these are mostly differences in behaviour and associated underlying processes, such as personality traits or intelligence. In music psychology studies, individual differences may include music preferences, everyday music use, music-induced emotions, musical aptitude and so on (Vuoskoski, 2014a).

In studies on bodily responses and body movement to music, personality traits are one of the most frequently studied individual differences. They can be defined as dispositions to behave in particular ways in certain situations that are relatively stable throughout the lifespan (Vuoskoski, 2014b). For example, 'friendly' or 'shy' are common language descriptors of some personality traits. In psychology studies, personality traits are often classified according to a five-factor model (John & Srivastava, 1999):

- Openness to Experience: opposite to closed-mindedness; having a deep, complex and original experiential and mental life
- Conscientiousness: tendency for well-thought, organised behaviour, impulse control and following norms and rules
- Extraversion: an enthusiastic approach to social activities, assertiveness and positive emotionality
- Agreeableness: connected to prosocial orientation, altruistic behaviour, modesty and trust
- Neuroticism: a tendency to feel anxious, nervous, sad and tense

Some studies, although scarce, show how personality traits and other individual differences link with the different features of movement to music. There is also evidence that some people are more prone to specific types of bodily responses to music than others. But how about movement responses? Is it possible to predict what kind of person will respond to music with a particular type of body movement?

This section has focused mainly on two types of individual differences: (a) psychological characteristics, and (b) music-related preferences and behaviours. The following sections summarise the most relevant studies on individual differences in the context of physiological responses and body movement to music. There are, of course, other individual differences that come into play (e.g., cultural and socio-economic), but these types of differences are not discussed in this thesis.

3.2.1 Individual Differences in Bodily Responses to Music

As discussed in Section 2.2.2, music can elicit various physiological and physical responses in the human body. However, these responses vary between people in numerous ways. For example, people might differ in how responsive they are to music: how much stimulation is needed to elicit a response, and how large the response is. The same kind of music can also elicit different *types* of bodily responses among people. Moreover, these responses might depend on various types of music preferences. These could include preferences concerning the music (e.g., genre or instrumentation) and also the way of listening to music (e.g., loudly on headphones). Such individual differences—which are often not accounted for in empirical studies—make studying bodily responses to music challenging.

In a study involving almost 1,000 people, Gabrielsson (2011) collected participants' stories about strong experiences associated with music, including various bodily responses. About 24% of participants reported crying in response to music (28% female and 18% male participants), 10% experienced shivers and shudders (12% male and 9% female), and 5% reported the occurrence of piloerection (i.e., goosebumps; no data on gender). There were also reports of other, less commonly experienced, physiological reactions: tingling sensations, relaxation or tension in the muscles, warmth, changes in breathing, heart palpitations, trembles, sensations in the chest and stomach, lump in the throat, dizziness, nausea and even pain (Gabrielsson, 2011). These self-reported experiences are in line with meta-analyses of bodily responses to music by Hodges (2008, 2010) (see Section 2.2.2). Looking at the percentage values, however, we can see that the experiences are not universal: people respond to music differently.

There are similar self-report studies that focus particularly on physiological responses to music, and most often, those associated with music chills: pupillary dilation, shivers, tears and goosebumps. Several of these studies show significant differences in how—and whether—people experience such sensations. Notably, some people declare never having gotten chills when listening to music (Nusbaum & Silvia, 2011). There have been several attempts to identify traits that are related to a tendency to have such reactions. Experiencing chills in response to music and other forms of beauty was shown to be associated with Openness to Experience (McCrae, 2007; Silvia & Nusbaum, 2011; Nusbaum & Silvia, 2011). This trait is associated with a recurrent need to enlarge and examine experience (McCrae & Costa, 1997, p.826), and a deep, complex and original experiential and mental life (John & Srivastava, 1999). When compared to the other four personality dimensions, and also with music preferences, it was shown to be the single reliable predictor for the experience of aesthetic chills (Silvia & Nusbaum, 2011; Nusbaum & Silvia, 2011).

Apart from self-report methods, it is possible to study aesthetic chills using various physiological measures. Several studies on pupillary responses to music have demonstrated differences in people's experiences of chills. Gingras et al. (2015) showed that a greater self-reported role of music in one's life was associated with larger pupil dilations when listening to excerpts of music. Moreover, in their study, male participants exhibited larger dilations than females.

In a similar study by Laeng et al. (2016), participants reported having chills more often in response to self-selected songs than to control songs. Moreover, an interesting relationship between music chills and personality traits was observed. The Spirituality and Anger dimensions of the Affective Neuroscience Personality Scales (ANPS) by Davis & Panksepp (2011) were shown to affect the frequency of pupillary dilations during chills: positively for Spirituality, and negatively for Anger. The Spirituality dimension is defined as 'feelings of connectedness with all of life and oneness with creation', whereas the Anger dimension relates to 'feeling hotheaded, being easily irritated and frustrated, and expressing anger verbally or physically' (Davis & Panksepp, 2011). Thus, perhaps individuals who experience life as positive and meaningful, rather than as stressful and irritating, are more prone to aesthetic chills.

Last but not least, in a study on pupillary responses to low-groove and high-groove music, Bowling et al. (2019) observed gender-based differences: females exhibited stronger pupillary responses than males, in contrast to the findings of Gingras et al. (2015). Moreover, the differences in responses to low-groove and high-groove music were more notable in males. These findings regarding gender-based differences might be relevant to the topic of interpersonal differences in movement responses to music.

In sum, the identified studies on individual differences in bodily responses to music deal mainly with several types of physiological responses belonging to the category of musical chills. Much less is known about the characteristics of the listeners that can explain their physical responses to music.

3.2.2 Individual Differences in Body Movement to Music

Even though the link between movement and music seems to be universal (Sievers et al., 2013), people move to music differently. To some extent, movement may have to do with people's musical aptitude: their overall sense of rhythm, musical imagination, music and dance training, etc. Their movement can also depend on their fitness levels or body morphology (Dahl et al., 2014). Furthermore, in the last two decades, researchers have managed to link psychological attributes, such as personality and empathy traits, with some features of body movement to music.

In a series of studies, Luck et al. (2009, 2010, 2014) compared motion capture recordings of free dance to music with self-report personality measures, and found that different movement patterns can be associated with different personality traits. For example, they found that Neuroticism was positively associated with small, jerky and accelerated movements of the head, hands, feet and centre of mass (Luck et al., 2009, 2010), but negatively with larger, dynamic movements of body parts and overall kinetic energy (Luck et al., 2010, 2014). In turn, Extraversion was linked to fast movements of the head, hands and centre of mass, and overall, a higher amount, speed and energy of movement (Luck et al., 2009, 2010, 2014). They also found that Openness and Agreeableness were associated with smooth movements, and that Conscientiousness was connected to higher speed of movement, although throughout their studies, the results for these traits became less clear (Luck et al., 2009, 2010, 2014).

In a similar type of study, Carlson et al. (2016) used artificially time-stretched songs and showed that high Extraversion and low Conscientiousness were associated with greater responsiveness to small tempo changes during free dance. There were no significant relationships between the other personality traits and features of movement, although it should be noted that this study employed a fairly limited personality measure. Taken together, the findings of Luck et al. (2009, 2010, 2014) and Carlson et al. (2016) reveal interesting relationships between personality traits and movement to music. Currently, there is stronger empirical evidence for some personality traits (mainly Extraversion, but also Neuroticism), while the evidence for others (Openness to Experience, Agreeableness and Conscientiousness) is weaker or less consistent.

Some studies suggest that *empathy*, just like personality traits, is linked with certain aspects of body movement to music. Empathy, as a concept, has evolved in different ways over the last century (Silverman, 2014; Clarke et al., 2015), but in general, it can be defined as an individual's responsiveness to the other (Davis, 1983). Empathy has been shown to modulate neural responses to musical sounds, including increased activity in sensorimotor areas (Wallmark et al., 2018). In studies on body movement to music, Bamford & Davidson (2017) found that participants who scored high in empathy adapted their movement faster to tempo changes in the presented music stimuli. The high-empathy participants also reported that they enjoyed dancing more than participants with low empathy scores. Moreover, Carlson et al. (2018) found a positive relationship between empathy and responsiveness to the movement of the dance partner.

But why would empathy improve synchronisation of movement to music? While the answer to this question is still not clear, some researchers suggest that music can function as a virtual social agent involving social attuning and empathic relationships (Leman, 2008, p.126), and that even solitary music listening is a social experience (Launay, 2015) (see Section 3.3.2). If listening to music is a social activity, then empathy, which entails high responsiveness to social cues, can give people an advantage while engaging and interacting with music.

Movement to music can also depend on personal preferences and familiarity with the music stimuli. Some music features seem to be similarly appreciated by people; for example, the preferred tempo for dance music is typically in the range of 120–130 BPM (Moelants, 2003). Other aspects of music, such as genre, instrumentation or the content of low frequencies, can be a matter of personal taste. In fact, the experience of groove largely depends on a preference for and familiarity with the music stimuli, which can predict the groove experience better than any music-related feature (Senn et al., 2018). Interestingly, Luck et al. (2014) found that preference for the music stimuli had an U-shaped relationship with the amount of observed movement in a free dance task: participants moved the least to music that they liked moderately, and more to music that they particularly liked or disliked. Music that was well liked was, however, associated with the highest amount of movement overall. The same study also found interesting relationships between preferences, movement and personality: the U-shaped patterns between preference and movement were most pronounced in individuals who scored high in Neuroticism, less so for high scorers in Extraversion and Openness to Experience, and least pronounced for those who scored high in Agreeableness and Conscientiousness. These studies show the intricate connections between various types of individual differences and how important they are for understanding movement to music.

3.3 The Context of Music Experience

Apart from the features of music and the individual differences between people, there is another important factor: the *context* in which the music experience takes place. There are many possible situations and scenarios for experiencing music. Take the club setting, for example, where music is usually played very loud in a fairly dark room, with a crowd of excited people around. In such a setting, body movement is not only welcome, but may even be expected. Now, imagine a doctor's waiting room, where music is played quietly through a cheap speaker, in a brightly-lit clinic corridor, with many other people waiting quietly nearby. Compare these two scenarios to using headphones on a rush-hour bus ride, where the music blends with the noises of the vehicle and the people nearby. In all these situations and countless others, one can experience the same music track and respond to it in various ways.

Sometimes, a single factor in the context of music experience can play an important role. For example, in the music club scenario described earlier, if someone turned on the lights, the whole experience would change drastically. Also, listening to loud music for several hours while driving could be either unbearable or delightful, depending on the sound system, the current mood of the listener and whether they chose the music themselves. It is difficult (or perhaps impossible) to fully break down the context of music experience into a number of factors, especially given that they can change from minute to minute and with a shift of mood. However, one could try to group them into several categories:

- Sound features: sound level, sound quality, whether the music is being played live or from a record, what tools are used to distribute and play the music, what music was played before, etc.

- Social context: whether the music is experienced alone or with others, whether it leads to communication between listeners or perhaps with the performer, whether the specific music culture is familiar, whose choice it was to play the given music, etc.

- Physical environment: it can be at home, in a public space, dark or light, static or moving, etc.

- Psychosomatic factors: these are directly related to the present physical and mental state of the perceiver; for instance, whether they are comfortable, whether they want to listen to music, what mood they are in, etc.

To further complicate the problem, all these factors are interconnected in different ways, and can appear in multiple categories.

Because every listening context comprises multiple factors, it can be challenging to design experiments to study only one particular factor of the music experience context. Even in highly controlled laboratory settings, it is impossible to provide a de-contextualised experience or to control for all contextual factors. One way of approaching experiments that involve listening contexts is to include two different listening sessions and manipulate only one specific aspect of the context. However, this is also not entirely possible, as repeating listening sessions already gives a context of listening to the same music repeatedly. Other factors, such as growing tiredness, can also interfere.

All in all, studying the contexts of music experience empirically is difficult. Perhaps for this reason, it is not often done in embodied music cognition studies. There are, however, some studies that show how the context of music experience can be reflected in the bodily responses and movement of listeners. These will be discussed in the three following sections.

3.3.1 In or Outside a Laboratory?

Experiments on body movement to music, particularly those involving the use of motion capture or other movement-sensing technologies, are typically conducted in laboratories. The purpose of most music research laboratories that involve human subjects is to study music-related behaviours in a controlled setting. The benefits of conducting studies in a laboratory are plenty. For example, there is no need to carry around heavy and fragile equipment (sometimes this is not even possible, as in the case of MRI machines or some types of force plates). It is possible to create a quiet, secure environment with a minimal risk of visual and auditory distractions, and optimal conditions for recording high-quality data (e.g., motion capture recordings require a highly controlled setup).

On the other hand, the problem with laboratories is that people do not experience music in such settings in everyday life. The way things function in the laboratory might not necessarily reflect how things function in the real world. The presence of technical equipment, the detached and unnatural arrangement of the space and the presence of researchers can make the whole experience of music highly unrealistic.

Another problematic assumption is that the listening environment across different laboratories is fairly similar. In reality, numerous factors can influence the experience:

- Space: room size, space available for movement, texture of the floor and distracting objects
- Microclimate: air quality, temperature and lighting conditions
- Equipment: quantity and quality of equipment, and whether it feels restrictive, invasive or neutral
- Acoustics: ambient noises, reflections and resonances
- Presence of the experimenters: control room inside or outside the laboratory

Even though researchers are often aware of these problems, there is no simple way of controlling the impact of the laboratory setting. Neither are there standardised ways of documenting the setting so that experiments can be carefully replicated elsewhere.

To provide a more ecological experience of music, several research groups have attempted to study movement and bodily responses to music outside of the laboratory. For example, Luck & Toiviainen (2006) studied how ensemble musicians synchronise with the conductor's gestures by using the motion capture system at a music academy. Closer to the subject of this thesis, Styns et al. (2007) compared how people synchronise their steps with music or a metronome track while walking (see Section 3.1.3 for findings). They did so by measuring the participants' walking speed (with a GPS device) and tempo (by recording the sounds of footsteps with an MP3 recorder attached to one shoe) while they walked on an open-air athletics track.

Similarly, Franěk et al. (2014) measured the spontaneous synchronisation of walking speed and tempo with music while participants walked around a city. Here, participants had a small fisheye video camera attached to a belt on their waists, to record the movement of their feet and arms, as well as the surrounding environment. In such studies, it is hard to control for the impact of visual or social cues, or even the weather (Franěk et al., 2014).

Other researchers have attempted to create a more realistic environment for experiencing music inside the laboratory. For example, Solberg & Jensenius (2016) manipulated the laboratory lighting conditions to study body movement to EDM: the main lights were switched off, and rotating, colour-changing disco lights were used to create a club-like atmosphere. They also conducted the experiment in the evening and used high-quality speakers to play real, loud dance music for participants dancing in groups. To my knowledge, there are no studies that have compared whether such manipulations of the laboratory environment, or studying movement outside of the laboratory, produce different results to standard laboratory experiments on body movement to music.

It is difficult to tell whether it is possible to study movement responses to music reliably in the laboratory. While it is certainly easier to collect high-quality data on small-scale movement in laboratories, spontaneous movement might be a phenomenon that appears only in particular situations, which, again, differ between people. Moving to music, just like singing, can for some people be a form of expression that they would only engage in when they feel safe and free from judgement. For example, some people are most comfortable moving to music only when they can blend into a crowd. Others would rather move to music when they are alone at home. Still others do not feel embarrassed to move or dance in public spaces, even to music only they can hear; for example, some people may be comfortable playing air instruments while listening to music on their headphones at a bus stop. Therefore, it is possible that for some participants the laboratory environment seems unnatural or intimidating, while others feel safe and can forget that they are taking part in an experiment.

Studying spontaneous movement responses to music in realistic settings, e.g., during a concert at a music venue, has not been done extensively so far. As mentioned before, recording movement (especially of small magnitude) outside of the laboratory poses technical difficulties. However, there are certain music research laboratories that resemble music theatres, such as ArtLab[1] at the Max Planck Institute for Empirical Aesthetics and LIVELab[2] at the McMaster Institute for Music and the Mind. Such laboratories allow for studying responses to music in realistic settings. For example, Swarbrick et al. (2019) studied participants' head movements to new songs by a Canadian rock band. Participants listened either to the band playing live or to recordings of the same songs. This study showed that live music engages listeners to a greater extent than pre-recorded music, as reflected in faster head movements in the former listening condition. The audience members' degree of familiarity and connection with the band's music was also reflected in the intensity of head movements, and even in the accuracy of movement synchronisation with the beat in the music. These findings show not only important differences between listening to live and pre-recorded music, but also that the social context is crucial when studying movement to music.

3.3.2 Alone or Together?

Music most likely evolved as a social activity (Cross, 2001). Only recently, thanks to the development of recording and playback technologies, it has become possible to listen to music in solitude. How does a solitary experience compare to a shared experience in terms of embodied music cognition? Does the physical presence of other people influence how the human body responds to music?

To quantify the impact of social interaction on body movement to music, De Bruyn et al. (2009) designed a study in which children and teenagers were asked to move to the beat of the music in two conditions. In the social condition,

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[1] https://www.aesthetics.mpg.de/en/artlab/

[2] https://livelab.mcmaster.ca/

participants moved to music in groups of four, and in the individual condition, they were separated from one another by screens. Participants moved more in the social condition. Moreover, teenagers in the social condition synchronised better with the music compared to when they moved alone. Although these results make sense intuitively, it should be noted that movement in the individual condition might have been constricted by the close proximity of the screens. In another experiment on children, Kirschner & Tomasello (2009) examined whether there were differences in synchronising drumming movement with a human partner, a drumming machine, or drum sounds coming from a speaker. They found that drumming with a partner facilitated better synchronisation compared to the two other conditions.

One possible explanation for the previously mentioned results can be found in the theory of 'muscular bonding' (McNeill, 1997). This theory suggests that rhythmical, synchronous movement with others results in a shared euphoric feeling, which can be observed in many synchronous types of movement in human history (for instance, dance, military marching, the synchronous work of sailors or movements at religious ceremonies). However, this theory refers to explicit, overt and voluntary movement. It does not predict whether such a synergetic experience is possible when sharing a task associated with movement, but without actually performing the movement. Would muscular bonding occur if two people only imagined that they were moving together in synchrony? Furthermore, would listening to dance music together without dancing lead to muscular bonding?

The theory of *motor resonance* by Launay (2015) suggests that even solitary music listening is a social experience, because of the implied agency in the musical sound (compare with music as a virtual social agent; Leman, 2008, p.126). Motor resonance can happen when we see a person producing the sound, or when we associate the sound with specific body movements. Moreover, even without these associations, motor resonance can happen through the activation of motor regions of the brain by listening to rhythmical sounds (Overy & Molnar-Szakacs, 2009). Thus, listening to music (even alone) can be seen as similar to perceiving and processing the actions of another person, through the process that Godøy (2003) refers to as *motor-mimetic* cognition: automatic associations of sound with the body movements that they are likely to have resulted from.

3.3.3 Headphones or Speakers?

Another context worth considering is the technology used for creating and delivering audible sound. This includes all the technical tools that are used to play sound: storage media (CDs, hard drives, vinyl records and cassette tapes), amplifiers, speakers, etc. The technologies impact the musical sound in many ways, and several of these can be easily spotted even by amateur listeners—for example, the characteristic soft scratch noises of vinyl records. Expert listeners can, to a much greater extent, identify the particular technologies involved; some claim that they can even distinguish between the audio cables used for transmission. In most cases, however, the most defining part of the audio signal chain is the technology used to produce and distribute sound waves to the listener: headphones or speakers.

While there is a plethora of headphones and speakers available, I will not go into great detail about them. Before comparing the different types of these devices, it would be good to understand the general differences between headphones and speakers in terms of their impacts on bodily responses to music. Surprisingly, little is known about these impacts. Various studies have explored the differences between headphones and speakers in terms of evaluating various aspects of sound, interpreting messages conveyed by speech, listening fatigue and other topics. When it comes to bodily responses, however, the only study I have found is on listening to speech (Kallinen & Ravaja, 2007). The researchers found that listening to the news on headphones elicited more positive reactions (indicated by the activity of face muscles) and higher attention levels (indicated by changes in blood pressure) than listening to the same news on speakers. Moreover, depending on the listeners' personalities, reactions to speech played on both types of devices varied.

Other studies show that using headphones and speakers results in different perceptions of musical sound in each case. For example, Koehl et al. (2011) showed that while both types of devices seem suitable for the assessment of subtle differences in music records, the preferences for recording techniques were different when listening on headphones versus speakers. In this study, judgements of music excerpts were also more consistent between participants when they used headphones. Another study showed that participants had varying preferences for loudness and bass levels when using headphones and speakers (McMullin, 2017). Furthermore, confirming common knowledge among audio engineers, King et al. (2013) found that monitoring music on headphones and speakers affected the resulting sound mix. These and other studies suggest that using headphones or speakers significantly impacts listeners' experience of sound. Still, in embodied music cognition research, these two technologies are often used interchangeably, with little description of and justification for the particular choice of setup.

How can the playback method impact the embodied experience of sound? Several aspects of the design of headphones and speakers are worth considering. I suggest grouping them into five categories:

- Acoustic: the distribution of the sound signal. For example, a stereo image of speakers is more realistic; with headphones, the sound signal is split between the left and right ears.
- Physiological: the direct impact of the sound on the body. Speakers allow for a vibrotactile experience, particularly at high sound levels, while headphones deliver sound directly to the ear canal. Headphones also cover the ears of the listener; this has been shown to influence the functioning of the vestibular system and disrupt balance (Kanegaonkar et al., 2012).
- Physical: the placement of the device in relation to the body. Headphones are wearable; they are put on or even inside the body. They often have a

cable, which restricts movement.

- Aesthetic: the interpretation of sound. Via headphones, voices can be perceived as more intimate, as they are directed into the listener's ears. Features of sound resulting from parameters of the playback device can be misinterpreted as being features of the music record. Headphones can allow for deep immersion in the sound by cutting off distractions.
- Social: the impact that both devices have on communication with others. Headphones create a barrier in the acoustic space between people, while using speakers results in a shared experience of sound.

I believe that the use of headphones versus speakers is a particularly interesting factor in studying the context of music experience. Although their different design and acoustic properties are perhaps the most apparent, the consequences of using headphones or speakers for a music experience are multidimensional. If well understood and controlled for, the differences between these two devices can be taken advantage of and used to explore other types of listening contexts.

Chapter 4

Methods

4.1 Introduction

The experiments presented in this dissertation were both challenging and educational in terms of methodology. The five selected papers present data from four different experiments. These experiments were part of a larger project that also involved other experiments not included in this dissertation. Moreover, some analyses were done on data from experiments that took place before the project that I have been working on—Human Bodily Micromotion in Music Perception and Interaction (MICRO)—commenced in 2017. The main goal of this chapter is to show how the different experimental paradigms were developed, and how various technologies were explored in the process.

Over my fellowship period, I have been involved in the development of four experimental paradigms:

1. Championship of Standstill
2. Headphones/Speakers
3. MusicLab
4. Self-playing Guitars

In this dissertation, only papers based on the first two experimental paradigms will be presented. This chapter will explain in detail how these experiments were developed and conducted. Before delving into that discussion, I will briefly describe the two other experimental paradigms, since they constituted an important part of my work during the fellowship period.

MusicLab was developed in 2017 and is an ongoing project between RITMO and the University of Oslo Library. It has proven to be a great platform to combine data collection with the dissemination of research and entertainment. The project takes the form of public events: concerts in various venues, preceded by panel discussions with experts on given topics, and followed with live analyses of the recorded data. Several editions have been conducted and more are being planned. So far, only data from the first edition of MusicLab has been published (Gonzalez-Sanchez et al., 2018). This paper was not included in this dissertation for two main reasons: it is based on data from a very small sample of participants, and the data were collected outside the laboratory, resulting in limited experimental control. It was a fairly exploratory analysis that was qualitatively different from the other papers presented herein. Therefore, since it is not a formal part of this dissertation, the methodology of this and other MusicLab experiments I have participated in will not be discussed in this chapter.

The self-playing guitars are part of an artistic project initiated to explore several ideas. First, it explores the idea of using micromotion to control and interact with musical instruments (see also Jensenius et al., 2017a). Second, it functions as a platform for researching the boundary between digital and acoustic sound. At the core of the project there are six acoustic guitars, each equipped with a Bela micro-computer. There is also an actuator glued to the back of the guitar body. The Bela micro-computer is programmed to send signals producing electronic sound through the actuator, which results in a vibration of the guitar body and the amplification of sound through the resonating instrument. Several versions of the self-playing guitars were developed, depending on the types of sounds they made and how they interacted with each other and the perceiver. The diverse set-ups were presented as sound installations and musical performances during events in Oslo (e.g., at the Botanical Garden at the University of Oslo, the Ultima Oslo Contemporary Music Festival, and the Technology & Emotions Conference) and abroad (at the Tampere Conservatory, Finland). Apart from such dissemination activities, several research articles came out of this project, of which I co-authored one (Gonzalez et al., 2018). Since the exploration of the self-playing guitars was on the side of my own project, I decided to not include that paper in the dissertation.

Next, I will move on to a more detailed description of the two experimental paradigms that formed the basis of the papers included in this dissertation: Championship of Standstill and Headphones/Speakers. The goal is not only to describe the methodologies used in the papers, but also to provide some ‘backstage’ information on how the experiments were designed. The last section of this chapter will cover the methodology for the analyses on which the five publications are based. The different stages of organising and pre-processing the data are presented for each method separately, followed by descriptions of the statistical analyses performed on these sets of data.

4.2 Experimental Paradigms

All the papers that comprise this dissertation are based on experiments that belong to one of the two different paradigms. Both are discussed below.

4.2.1 Championship of Standstill

The idea for the Championship of Standstill paradigm came from an interest in using motion capture to examine how still people can stand (Jensenius 2014), and whether music affects human standstill. This led to the creation of a research paradigm in which data from a large number of people are collected when they try to stand still in two conditions: in silence and while listening to music. If people move more in the latter condition, despite trying to stand still, it would provide empirical evidence for the common assumption that music makes us move, and that it is indeed difficult *not* to move to music. In order to test this assumption, a research experiment under the public name ‘Norwegian

Championship of Standstill' was carried out, first in 2012, and then several more times in the following years. The data that were collected in the first two editions of the experiment, in 2012 and 2015, were not analysed until the MICRO project was started in 2017. Since then, new editions have been conducted in 2017, 2018 and 2019, using various types of stimuli and laboratory set-ups (see Figures 4.1, 4.2 and 4.5).

In this experimental paradigm, groups of participants are invited into the motion capture laboratory for a short experiment (of about 15–20 minutes). They are asked to stand as still as possible for 6–8 minutes (the timing varies between experiment editions). Approximately half the time is spent in silence. In the remaining time, various types of music and rhythmic stimuli are played on speakers. Further information on the arrangement of the silence and music segments, the types of stimuli used, the duration of the experiment, and other metadata for all Championships conducted so far are presented in Table 4.1. Each participant wears a reflective marker on their head. In order to measure how much the participants move their heads, this marker is tracked by a system of infrared cameras mounted on the walls and ceiling. After the experiment, participants are asked to fill in a short questionnaire. When one group finishes all the necessary procedures, there is a short break during which the experimenters prepare the laboratory for the next session. Then, the next group of participants is invited for a new recording session.

The Championship of Standstill has been conducted annually since 2017; each time, the laboratory set-up and stimuli were thoughtfully redesigned. All the editions conducted so far took place during the annual Open Day at the University of Oslo, during which prospective students are invited to visit campus. The participants were recruited largely from passing visitors who had come to get an overview of the activities taking place at the Department of Musicology. This recruitment process dictated several features of the experimental design. The experiment needed to be short in order to encourage visitors to participate, and a large number of participants had to be recruited and tested in one day. This meant that recording sessions took place every hour or even every half-hour. In order to collect data from as many people as possible within several consecutive hours, participants were tested in groups. Around 100 participants per Championship were recruited to take part (see Table 4.1). Because of this design, only head movement were recorded and analysed (this is further explained in Section 4.2.3), and all procedures, including the questionnaire at the end of the experiment, had to be condensed because of time constraints.

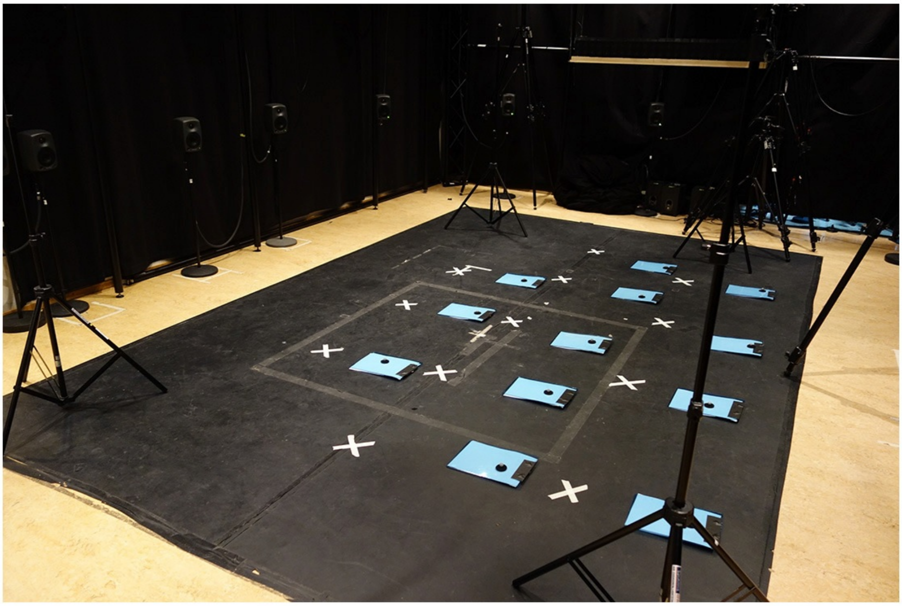

Figure 4.1: The floor of the motion capture laboratory prepared for the Championship of Standstill experiment (2018 edition). White crosses taped on the floor mark spots for participants to stand on, maintaining the necessary distance between them and ensuring that they stand within the view of the cameras. On blue clipboards there are printed copies of the consent form (to be filled in before the recording session) and a short questionnaire (to be filled in after the recording session). On the top of each board, a single reflective motion capture marker is glued to a circular piece of Velcro. Participants are asked to place the marker on the top of their heads themselves (if necessary, the experimenters are available to help). In the corners of the black mat there are four tripods, each with a marker mounted on top, approximately at the level of the participants' heads. Data from these markers are recorded to monitor the noise levels in the captured data. The two other visible tripods (on the right edge and upper-right corner of the photo) are used to mount two of the motion capture cameras.

Table 4.1: All Championship of Standstill editions to date. The speakers used for all the editions were Genelec 8020s; if a subwoofer was used, it was a Genelec 7050. The questionnaires are described in detail in Section 4.3.3. The exclusion criteria, if specified, were hearing loss, neurological disorders, arthritis, orthopedic conditions, recent injuries and balance disorders. In 2019, having participated in any of the previous Championships of Standstill was also included in the exclusion criteria.

Year	Participants Tested	Group Size	Participants in Analyses	Duration	Stimuli	Silence Segments	Mocap System	Playback	Questionnaires	Exclusion Criteria	Publications
2012	100	5 to 17	91	6 min	A variety of genres	3 min silence, 3 min music	Qualisys	2 speakers and subwoofer	Basic	None	Paper I
2015	108	3 to 12	Data not analysed	6 min	EDM, Salsa, Meditation	Randomised (1 min)	Qualisys	24 speakers	Basic	None	None
2017	71	3 to 13	71	6 min	EDM, Telespringar, Indian	Alternating (1 min)	Qualisys	2 speakers and subwoofer	Basic	None	Paper II
2018	110	5 to 13	87	8 min	EDM, Drum track, Beat track	Alternating (30 sec)	Qualisys	4 speakers	Basic	Specified	Paper A
2019	116	4 to 8	98	8 min	Drum tracks, Beat tracks	Alternating (30 sec)	OptiTrack	2 speakers	Basic + IRI	Specified	Paper V

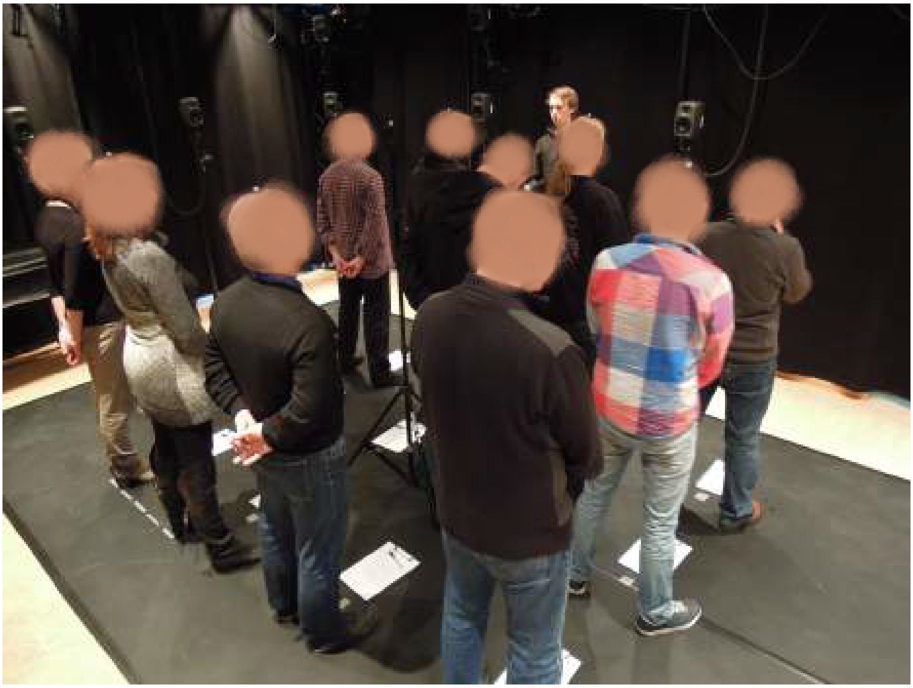

Figure 4.2: A group of 10 participants and one experimenter facing the participants, providing an instruction before the recording session (2012 Championship of Standstill edition). See Appendix A for the instruction script. Participants are encouraged to stand in any position they find comfortable. In the middle of the group stands a tripod with a reference marker on top, approximately at the level of participants' heads.

4.2.2 Headphones/Speakers

Headphones and speakers are two popular, but very different, tools used to play recorded music. The main difference between them—that inspired this experiment—is in the way they transmit sound energy to the human body: either directly to the ear canal, or from distance, allowing not only auditory but also vibrotactile perception of sound. Considering this and several other differences between headphones and speakers (discussed in Section 3.3.3) made me wonder how bodily responses to music, including movement, can differ depending on whether headphones or speakers are used.

The experimental paradigm comprises two listening sessions, during which headphones and speakers are used to play music to participants (see Figures 4.3 and 4.4). Participants are tested individually and each of them is exposed to both listening sessions. The sessions are arranged in a counterbalanced order—half of the participants start with headphones and half with speakers. Each session

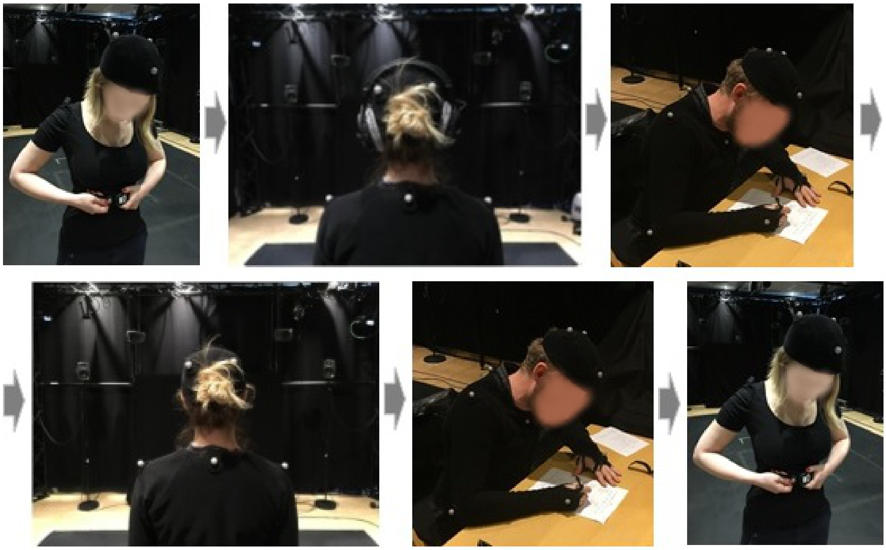

Figure 4.3: An illustration of the consecutive stages of the Headphones/Speakers experiment. From left to right: preparation, first listening session, first set of questionnaires, second listening session, second set of questionnaires and removing sensors.

takes eight minutes to complete and comprises alternating segments of silence and sound stimuli. The stimuli are presented in a randomised order and are each about 45 seconds long. Each participant is dressed in a motion capture suit with 20 markers attached to critical anatomical landmarks. Additionally, three other types of technologies are used to track bodily responses. Each participant is equipped with a breathing sensor placed on a band around the waist, and a set of six electromyography (EMG) electrodes placed bilaterally on the feet, forearms and shoulders to measure muscle activity. During the recording sessions, the participants stand on a balance board that recorded shifts in pressure distribution that correspond to postural sway.

There is no particular task to complete; participants are asked to stand in a neutral, comfortable position and listen to music. No explicit instruction about moving or not moving is given. After each recording session, participants are asked to fill in a large set of questionnaires. The total time of the experiment, including preparation, recording and filling in questionnaires, is about 1 hour and 15 minutes (with small variations depending on the time spent on preparation and questionnaires).

Preparing this paradigm took a substantial amount of time, and many decisions had to be made. For example, the types and number of different playback methods to be tested were considered. While the initial idea was to test various types of headphones (on-ear, in-ear, bone-conductive, noise-cancelling, etc.) and several configurations of speakers (a single speaker, stereo speakers, four speakers, a multi-speaker array, etc.), it soon became clear that this would not be possible within a single experiment. Since there was a lack of research on the effect of speakers and headphones on bodily responses to music, we decided to start by comparing the two most commonly used types of playback systems: around-ear headphones and a pair of stereo speakers. The main reason was that any more than two listening sessions seemed too tiring for participants and would have been difficult to conduct (there was also the potential problem of participants listening to the same stimuli multiple times).

Another decision that had to be made specifically for this experiment regarded the number of testing methodologies to be used. Unlike the Championship of Standstill paradigm, this experiment was conducted individually. This provided a good opportunity to test different types of data collection technologies. The primary methodology was tracking motion using an infrared motion capture system. But for the sake of methodological experimentation, I also decided to collect electromyography, breathing and balance data. There were several methodological questions that preceded this decision: how invasive is it for the participant? How long does it take to apply the sensors? What kinds of data can be obtained? Would such data inform the research question of the study? This experiment was fairly exploratory, and the main interest was in small-scale body movement associated with music listening, so it seemed interesting to test various approaches to measuring such movement. At the same time, it may have impacted the participants' comfort and their interpretation of the experiment instructions (see Section 6.3 in Discussion).

Before conducting the experiment, a pilot study was done on four subjects, who were also music researchers. All of them underwent the full procedure, including the filling-in questionnaires and collection of data from the breathing sensor, balance board and EMG. Their feedback about the experiment design was positive. They agreed that the music was played at a sufficient sound level, which was perceptually similar for headphones and speakers.

It is also worth noting that this paradigm (two listening sessions) can be useful for testing the impact of many other variables on body movement. These could be further comparisons between different playback systems (e.g., stereo speakers vs. an array of speakers, noise-cancelling headphones vs. standard headphones, subwoofer vs. no subwoofer, etc.) or different conditions (eyes open vs. eyes closed, disco lights vs. standard lights, etc.).

4.2.3 Comparison of the Two Paradigms

The two paradigms (Championship of Standstill and Headphones/Speakers) may seem conceptually similar since they are both based on recording the movement of a standing person while they listen to music. There are, however, important discrepancies between them. Table 4.2 shows some key differences between the two paradigms, which will now be discussed in more detail.

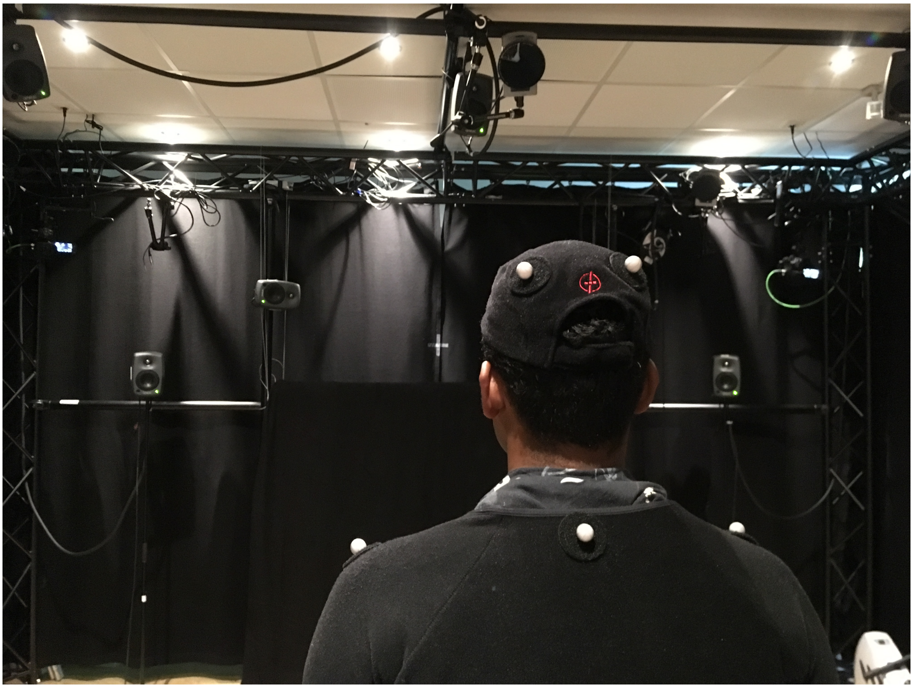

Figure 4.4: A photograph of a participant in the Headphones/Speakers experiment. Motion capture markers are attached to selected anatomical landmarks via a Velcro adhesive motion capture suit and hat. A pair of Genelec 8020 speakers (here, the pair at the level of the participants' ears) is used to present sound in the speakers listening condition. A white cross is taped to the wall (at eye level). One of the 12 motion capture cameras, facing the participant, is visible in the upper-middle section of the photo. At the level of the head markers, towards the left and right edges of the photo, there are two cameras recording audiovisual material for reference.

Sample size As the sample size increases, the risk of sampling biases and statistical errors decreases. That means that the Championship of Standstill experiments, which are based on larger participant samples than the Headphones/Speakers paradigm, produce more statistically sound results. Practically, it also means that excluding participants (for example, because of missing data points) is more problematic in an experiment with a smaller sample.

Group size It is much easier to account for the behaviour of one person than of a group. The latter requires the presence of at least two experimenters, especially when there is a tight schedule and given the different speeds at which participants fill in questionnaires. Moreover, if something goes wrong during a group recording session, the data from the entire group may have to be discarded.

For instance, during one of the Championships, one of the participants started laughing. This eventually led to other participants laughing, and the data for the entire group had to be discarded. There may also be subtler group dynamics at play that might be difficult to notice, but may become evident while comparing groups in the data sets. Testing several people at the same time also makes it difficult to collect data from body parts other than the head. This is because placing markers lower than the head may lead to marker occlusion by the surrounding participants. A minimum of three cameras need to detect the position of a given marker at all times, otherwise it is impossible for the system to recreate a three-dimensional space in which the markers were located, leading to missing data points.

Duration of the experiment The longer the experiment, the more time there is to record data. For example, in the Headphones/Speakers experiment, it was possible to collect data using many different questionnaires. In the Championships, given the time limit, the number of questionnaires had to be reduced to bare minimum. At the same time, the longer duration of experiments also has some disadvantages. First, it is more difficult to recruit volunteers for longer experiments, and it also requires more energy and time from the experimenter (not only at the stage of data collection, but also during data pre-processing, management and analyses). Moreover, the likelihood of participants getting tired or bored increases with time. This is especially true for these experiments, as participants are required to stand relatively still, i.e., without changing their position, stretching, etc. The recording sessions had to be only a few minutes at a time, and the duration of the whole experiment had to be just long enough that it would not put too much strain on the participants.

Number of listening sessions The Championship of Standstill had one listening session, while the Headphones/Speakers experiment had two. The latter allows for comparing movement between the two listening sessions, which can be an interesting way of exploring what types of factors influence behaviour. The participants, as well as the general circumstances of the experiment, were the same in both listening sessions. This eliminated the problems that occur when replicating an experimental paradigm after a certain amount of time. However, comparing two listening sessions in one experiment also poses some challenges. In the first session, participants were less familiar with the experiment, the laboratory environment and with the stimuli (if they listened to the same set of stimuli twice). This can cause a familiarity effect, which is likely to increase the participant's enjoyment of the stimuli (Peretz et al., 1998), but also perhaps their annoyance, if the stimuli are considered unpleasant. As for familiarity with the laboratory environment and experiment procedures, participants may, for example, feel more comfortable and relaxed in the second session, which can also impact the data.

Technologies One of the interests of the MICRO project is testing various technologies to see how they register micromotion and other subtle forms of movement. However, given the short duration and high intensity of the Championship of Standstill paradigm, it was not the best choice for this purpose. Placing sensors on the body, even if they are relatively non-invasive, requires some time and effort. If that has to be done for several participants at the same time, more time and assistance is required. Other obstacles include providing a sufficient number of sensors for a large group and avoiding problems associated with recording data simultaneously from multiple sensors. The latter can be particularly problematic when it comes to synchronisation and ensuring that the recording starts and stops at the same time for all devices, without any jitter or drift. We have also experienced many issues while using wireless devices, which may have to be turned on and off several times to connect and transmit data. Since there was no such time constraints for the Headphones/Speakers experiment, it was well suited to testing different sensing technologies.

Mocap markers In the Championship of Standstill experiments, only head movement was recorded, using one motion capture marker on the top of the head. In the Headphones/Speakers paradigm, a motion capture suit was used. This enables the use of any number of markers, depending on the level of detail in which one wants to map the movement of different parts of the body (see Section 4.3.2). For this particular experiment, the use of 20 markers was deemed suitable. Adding further markers would require more time, as each marker had to be placed on the same anatomical landmark (e.g., elbow or knee) for all participants. Because of anatomical differences between participants, this means repositioning the markers before each recording. Motion capture suits of different sizes were used, and even among suits of the same size, repositioning at least some of the markers was necessary. As explained previously, this kind of extensive set-up was not possible in the case of the Championships of Standstill. However, even in the case of the Headphones/Speakers experiment, some compromises had to be made in terms of the number of markers used and the level of detail of mapping participants' movement.

Questionnaires Due to the time constraints of the Championships, data collection from questionnaires had to also be kept to a minimum. However, in the 2019 edition of the Championship, we added a longer questionnaire. We asked participants to fill in the questionnaires in a room outside the laboratory; a research assistant was designated to take care of participants in that time. So while it is possible to include a larger set of questions and add more elements to the experimental procedure, it increases the time necessary to complete the experiment and can discourage participation. For the Headphones/Speakers experiment, not only was there less pressure on participants, but it was also much easier to attend to one participant at a time in case help was needed.

Task In both experiments, participants stood on the floor and listened to music while their movement was recorded. In the Championships, however, the task was to try not to move. In the other paradigm, there was no specific task; participants were asked to stand in a neutral position and listen to the music. They were neither instructed to remain still nor to move. The inclusion (or exclusion) of this instruction may seem like a subtle difference, but it significantly impacted our interpretation of the data. In the case of the Championships, we can say that the observed movement was involuntary (unless someone decided to give up on the task; but we have not encountered such cases) or against the participants' will. In the Headphones/Speaker paradigm, it was more ambiguous as to whether movement was voluntary or not.

Reward Each Championship of Standstill offered a universal gift card for 1,000 NOK (approx. 100 USD) to the winner. Participants were informed that only the person with the best score (the one who moves the least) would win the prize. Indeed, 1,000 NOK is more attractive than 200 NOK, but winning is not guaranteed and the chances of winning were not high. While these odds were somewhat discouraging, perhaps the competitive aspect of the Championship paradigm was more attractive to participants than the smaller, guaranteed financial gift. Either way, the type of rewards may have impacted participants' motivation to complete the task, which in turn may have affected the quality of data.

To sum up, the Championship of Standstill and the Headphones/Speakers paradigms were similar in many ways, but there were also substantial differences between them. As can be seen in the examples above, each paradigm had its own advantages and disadvantages, which largely contrast with each other. Considered together, these two paradigms can work in a complementary manner, allowing for either sufficient data collection from a large number of people or for an in-depth exploration of data from one person at a time. Future experiments based on both paradigms, with some variations in the design of the study, could help determine which aspects of music, personal characteristics and listening context contribute to spontaneous body movements that occur in response to music.

4.3 Data Collection

The main methodologies used for data collection were motion capture and self-report measures. However, in the Headphones/Speakers experiment, other types of technologies, such as electromyography (EMG), a balance board and a breathing sensor, were used. Since the data from these measures were not analysed, they will only be described briefly. The most important tools, together with the sound stimuli used to collect data, will be explained in detail in this section.

	Championships	**Headphones/Speakers**
Sample size	~ 100 participants	~ 35 participants
Group size	3 to 17	1
Duration	~ 15 min	~ 1 hour 15 min
Recording sessions	1	2
Technologies	Mocap	Mocap, EMG, balance board, breath sensor
Mocap markers	1 (head)	20 (full body)
Questionnaires	Basic	Extended
Task	Stand as still as possible	Stand and listen
Reward	1,000 NOK for the winner	200 NOK

Table 4.2: Main differences between the two experimental paradigms.

4.3.1 Sound Stimuli

Sound stimuli are a key aspect of the design of any empirical study on music listening. The results are likely to vary according to the type and quality of stimuli used. There are several possible approaches to designing stimuli for the experiments. One could, for example, use custom-made stimuli composed for the experiment, excerpts from existing music, or stimuli used in other experiments. The stimuli could be as highly controlled as possible, or as realistic as possible. Moreover, the stimuli could be highly movement-inducing, or the opposite. In fact, across different experiments, we have tried to test, or even combine, all of these approaches. This section will explain how the sound stimuli were selected, designed, prepared and played in the experiments.

Selection

The selection of sound stimuli was based on several ideas that changed over time. First, the interest was in whether there were any differences between the silence and sound conditions, and in the general differences between music genres (Paper I and Paper II, respectively). Second, the interest was in the differences between stimuli that have varying levels of musical and rhythmic complexity, and, generally, various musical features (Paper II, Paper III, Paper IV and Paper

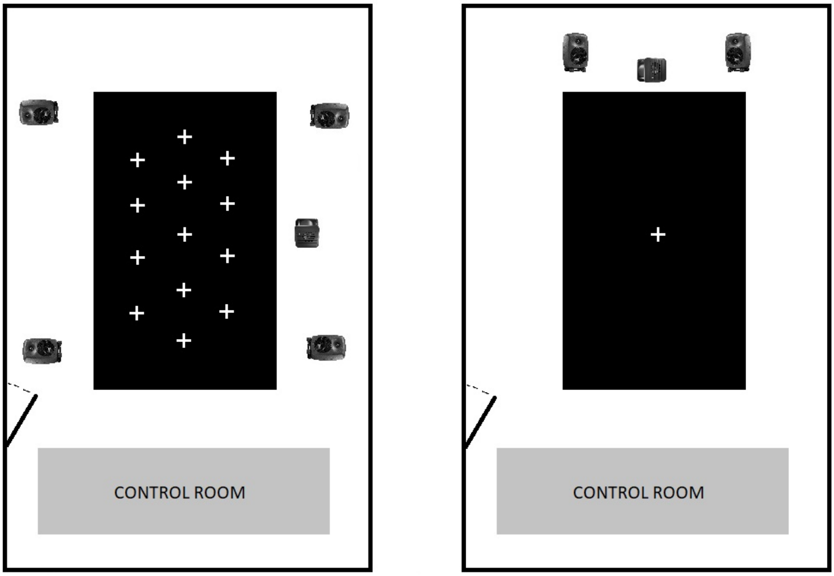

Figure 4.5: An illustration of the sound set-up in the Championships of Standstill (left) and in the Headphones/Speakers (right) paradigms. The black rectangle represents the capture space (the range of the cameras' point of view). White crosses represent points where participants stand (these varied between Championships editions). The doors to the lab, close to the control room, are marked. Over the years, there were variations in the set-up for the Championships. In 2012 and 2017, only two speakers and a subwoofer were used (the speakers were on the wall opposite the door), and in 2019, only two speakers, without a subwoofer, were used (the speakers were on the same wall as the door). In 2018, all four speakers, and no subwoofers, were used. In 2015, the full 24-channel array of lab speakers was used, but since the data from this experiment were not analysed, the corresponding set-up is not presented here.

V). There was a particular focus on comparing tracks that have metronome-like rhythms with tracks that have more elaborate rhythmic structures (Paper IV and Paper V). Third, another area of research curiosity was tracks that are specifically designed to make people move (all papers to a certain extent, but particularly Paper III, Paper IV and Paper V).

Based on the results of Paper I and Paper II, which showed that EDM (electronic dance music) induced a particularly high quantity of spontaneous movement, we decided to focus on this genre for Paper III and Paper IV. Paper V, on the other hand, had only self-designed stimuli that were based on drum samples. The motivation for using the particular stimuli is explained in each paper.

Preparation

The stimuli that were excerpts of existing music tracks were cut to the desired duration in Reaper DAW. The loudness between them was normalised by ear; in most cases, this did not require manipulating the original loudness level. Self-designed tracks were made in Reaper DAW using sound samples available online.

In most cases, the duration of a single stimulus was approximately 45 seconds, but in some studies, it was 20–40 seconds (Paper I), 30 seconds (Paper V), or one minute (Paper II). Some small variations in duration across stimuli within experiments were included to allow for the last bar or musical motive to finish. Across experiments, the reasons for using stimuli of different duration were mostly pragmatic: to include an optimal number of stimuli, but also not to bore participants in the case of simpler and repetitive stimuli in some experiments (Paper III, Paper IV and Paper V). The overall goal was to keep the listening sessions short and avoid tiredness and boredom significantly impacting the results. Optimising the duration of the listening sessions was crucial, as participants were expected to stand throughout the experiment (which can be more tiresome than sitting or lying down, and more boring than dancing). Thus, the duration of the listening sessions was between 6–8 minutes.

Presentation

Table 4.1 briefly summarises the differences in the Championship of Standstill editions, including in the types of stimuli, silence segments and playback systems. These aspects will now be explained in more detail.

In 2012, the motion capture recording session started with a three-minute silence segment, followed by a three-minute music segment. The music segment comprised seven short music excerpts, ranging from non-rhythmic orchestral music to electronic dance music (see Jensenius et al., 2017b, for details). The order of presenting the music segments was identical in each recording session (for each group of participants). A single .WAV file, with three minutes of silence at the beginning, and a compilation of tracks in the second part, was used.

For all experiments conducted since 2015, a custom-made patch running in the graphical programming environment Max (Cycling '74) was used to play the music stimuli in a randomised order. This allowed for precise synchronisation between the played audio files and the recorded motion capture data. The Max patch was triggered each time the recording session started in Qualisys Track Manager.

In 2015, three segments of music were used: Meditation, Salsa and EDM. The duration of each piece of music and each silence segment was one minute. The order of the music and silence segments was randomised, which resulted in various combinations. Two constants were that each recording started and ended with a silence segment, and that each type of music stimulus was only played once. Therefore, the possible combinations of music (M) and silence (S) segments were S-M-M-M-S-S, S-M-S-M-M-S, S-M-M-S-M-S and S-S-M-M-M-S, in which music segments (Meditation, Salsa, EDM) could be presented in any order. Data from this experiment have not yet been published.

In 2017, three segments of music were used: Telespringar (Norwegian folk dance music played on fiddle), Indian vocal music and EDM, each one-minute long. The order of the silence segments was fixed, and they alternated with music segments (S-M-S-M-S-M-S). Each recording session started and ended with 30 seconds of silence, and the two silences between music segments were each one-minute long.

In 2018, the sound stimuli were identical with those used in the Headphones/Speakers experiment (regarding the set of sound tracks and the order of presentation). There were six sound tracks used: four fragments of EDM music and two custom-made tracks composed of drum samples. The order of silences was fixed, and they alternated between music segments (as usual, each session started and ended with silence; S-M-S-M-S-M-S-M-S-M-S-M-S). Each sound track was approximately 45 seconds long, and each silence segment was 30 seconds long.

Finally, in 2019, the sound stimuli were self-designed and comprised six tracks. Three of them were 'metronome' tracks, based on the sound of a drum, and three were musical drumming tracks, also composed of drum samples. Each track was approximately 45 seconds long. There were three different tempi (90 BPM, 120 BPM and 140 BPM), and one pair of tracks (metronome and music) for each tempo. Each session began and ended with 45 seconds of silence. The other silence segments were 30 seconds long and alternated between tracks in the same manner as in the 2018 iteration.

Regarding playback method, there are two important aspects to consider across experiments. First is the type of device used to play the sound stimuli. Second is the arrangement of these devices in the laboratory. As displayed in Figure 4.1, for the Championships of Standstill in 2012, 2017 and 2019, music was presented using two Genelec 8020 loudspeakers that were facing the participants. For the Championship of Standstill in 2018, four speakers were used, which stood in the corners of the rectangular recording space. A Genelec 7050 subwoofer (a type of large speaker designed to reproduce low frequency sound) was used for the Championships of Standstill in 2012 and 2017, as well as for the Headphone/Speakers experiment. Low frequencies, when played sufficiently loud, can be perceived as vibrations in the body (McMullin, 2017); they also play an important role in body movement to music (Burger et al., 2017) and the perception of rhythm (Lenc et al., 2018; Stupacher et al., 2016). Thus, the use of a subwoofer was expected to increase the movement-inducing properties of the stimuli. On the other hand, the distribution of sound from the subwoofer standing on the floor in front of a group of people was most probably unequal between different participants in the same group. Those standing in close proximity to the subwoofer were more likely to feel its impact than those standing in the rows further away, given that rows of participants occluded each other. For this reason, the use of the subwoofer was abandoned in the later versions of the Championships. It should be noted here that this obstruction was less problematic for the Genelec speakers, which were either at or above head level in all experiments.

To conclude, the order of presentation of stimuli and use of audio equipment varied between the Championships. These changes, presented here in chronological order, reflect the evolution of the paradigm driven by the motivation to test different scenarios and to optimise the experimental procedure. In retrospect, it would perhaps have been better to be consistent between editions of the Championship, as these adjustments made it more difficult to compare results across iterations. However, given the otherwise coherent experimental design (comparing head motion in silence and to music), it was a good opportunity for testing and comparing different set-ups. Still, the changes should have been introduced in a more controlled and systematic manner.

4.3.2 Body Movement Measures

Body movement can be measured in multiple ways. Sometimes, studying participants' movement does not require any specific technology, and the systematic observation of behaviour is sufficient for collecting data (Phillips-Silver & Trainor, 2005, 2008). However, there are many useful technologies available to measure movement. In general, they can be grouped into video-based and sensor-based methods (Jensenius, 2018). Depending on the type of movement one is interested in and the analysis they want to perform, these two types of methods can be useful to varying extents.

In this dissertation, the main focus is on body movement that is rather minuscule and often impossible to perceive just by looking at the person. The goal was to observe the general amount of movement related to changes in posture (body sway or breathing related movement) and subtle responses typically associated with listening to music (head nodding, finger or foot tapping, etc). For this purpose, we used an infrared, optical, marker-based motion capture system—a technology that enables the collection of movement simultaneously from various parts of the body, and with high precision. The experiments described in this dissertation were all conducted using this movement measuring technique. To explore other possibilities, several other techniques were also tested in one of the experiments (Headphones/Speakers). These methodologies will be briefly introduced and described in the context of the dissertation' experiments. Their advantages and disadvantages in the given scientific scenarios will also be discussed.

Motion Capture Technology

The name motion capture (often shortened to 'mocap' or 'MoCap') is commonly used to refer to a specific type of motion capture technology, i.e., optical, infrared, marker-based systems (Jensenius, 2018). This technique of measuring motion is commonly used in studies on music-related body movement. However, there are other motion capture technologies available as well, which are primarily based on different types of sensors (magnetic, inertial, electrical, etc.). The main difference between marker-based and sensor-based motion capture solutions is

Figure 4.6: Left: Oqus motion capture infrared light camera from Qualisys. Right: A calibration frame and wand. (Photo: Qualisys)

that the former use optical systems based on video recordings, and the latter employ ways of registering movement that do not produce visual data.

Infrared, marker-based motion capture systems consist of an array of several infrared cameras (see Figure 4.6), usually at least six (Jensenius, 2018). Such cameras emit rays of infrared light and detect any reflections of that light from surfaces. Markers used in these types of systems are typically small balls covered in a highly reflective material, which makes them easily detectable by cameras. The disadvantage of this system is that the cameras often record not only reflections from the markers, but also other shiny surfaces, which results in artefacts in the data. Therefore, such recordings usually takes place in a highly controlled laboratory environment. Before the recording, it is important to remove or cover any other possible sources of reflections, such as sleek surfaces or reflective elements on clothes and objects. Reflective markers are often called passive markers, as they do not emit their own light. Sometimes, a good alternative is to use active markers, which are typically small LED lamps. The benefit of using such markers is that they can be seen from greater distances and in less controlled environments—for example, outdoors and in changing lighting conditions. However, more controlled environments allow for the collection of high quality and consistent data.

The more cameras there are in the system, the easier it is to accurately recreate the recording space for the system and get continuous (uninterrupted) data from each of the markers. Each camera is positioned at a different angle relative to the recorded object. Using triangulation, the images from all cameras are combined in order to track how the markers move in the three-dimensional space. At least three cameras need to see each marker at each time frame (typically, data are recorded at a high speed—100 Hz or more; Jensenius, 2018).

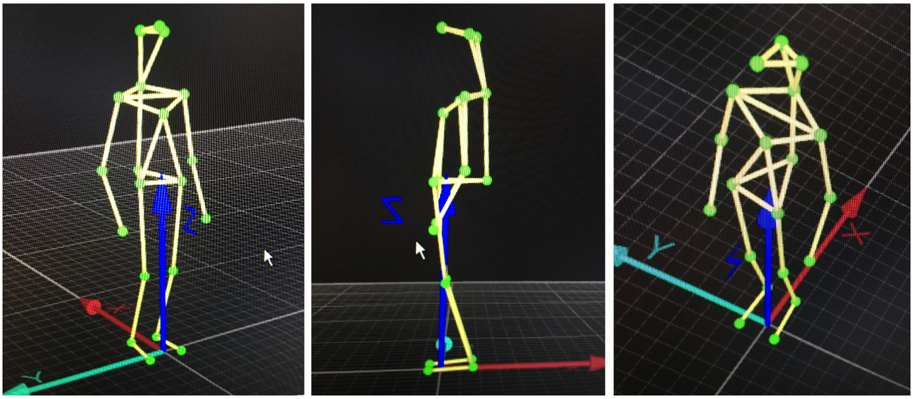

Figure 4.7: An example of a motion capture stick figure. Three different planes show the placement of the 20 motion capture markers on the body.

Sometimes, when the recorded agents move, reflections from some of the markers become temporarily occluded, and thus, invisible to a number of cameras. For more static recordings, as with recording micromotion, this is less problematic.

Motion capture systems are typically designed to track rather dynamic movement. They are useful for recording movement of people and animals for numerous purposes, such as, for example, creating a digital image of a moving body in a film or video game. Based on motion capture recordings, it is possible to build a virtual model of a moving person that is more accurate and realistic than one that uses digitally designed movement. Motion capture is also useful for medical purposes; for example, to track the progress of motor therapy by recording how the patient moves at various stages of convalescence. Moreover, motion capture is used in sports, to map and optimise the movements of athletes. These are all fairly large-scale movements of human and non-human bodies. In the case of subtle movement, such as micromotion—which is typically smaller than 10 mm/s—there is the risk that there will be more noise than actual movement data. Fortunately, good quality motion capture systems are able to record human body micromotion with sufficient resolution (Jensenius et al., 2012).

Motion Capture Apparatus

All experiments, apart from the 2019 Championship of Standstill, were performed using a Qualisys motion capture system with Oqus 300/500 cameras (see Figure 4.6). Depending on the experiment, 12 to 13 cameras were used, and the sampling rate was either 100 or 200 Hz (frames per second). One camera in the laboratory required servicing, but the repositioned array of 12 cameras proved sufficient for obtaining the same quality of data. The sampling rate is usually set based on the speed of the body movement being recorded, and on the spacing between the markers (Song & Godøy, 2016). Higher sampling rates

Figure 4.8: The motion capture laboratory where all the experiments took place (this is a picture from the Headphones/Speakers experiment). Several cameras and speakers are mounted on the walls, floor and ceiling. The floor is covered with a black matte material to prevent reflections from the yellow linoleum. The white tape on the floor is used for reference when placing the calibration frame on the floor (there are several configurations for different ongoing experiments in the laboratory).

are required to record faster movements (e.g., drumming), but they also result in a brighter image, thus increasing the likelihood of reflections from smooth surfaces being misinterpreted by the system as reflections from markers. To study micromotion and spontaneous movement to music, a sampling rate of 100 to 200 Hz seemed the most optimal. Considering that the scale of such body movement (and particularly micromotion) is very small, it was also important to question whether the system would be sufficiently accurate to register the scale of movement. If the resolution of the motion capture system is lower than the scale of movement, it results in artefacts, i.e., noise. Before the MICRO project started, Jensenius et al. (2012) confirmed that the resolution of motion observed in humans standing still is considerably higher than that of noise in good quality motion capture systems.

The 2019 edition of the Championship of Standstill was performed using an OptiTrack motion capture system. This was because the motion capture laboratory, where all previous experiments were conducted, was moved to a new building outside of the main university campus (where the headquarters of RITMO are located). A new laboratory was created in an emptied space and equipped with an eight-camera OptiTrack motion capture system (Flex 13) with a fixed sampling rate of 120 Hz. For this experiment, data were collected and pre-processed in OptiTrack Motive. For all other experiments, data were recorded and pre-processed in Qualisys Track Manager.

Before the experiment, the recording space had to be calibrated in order to set up a coordinate system that represented the three-dimensional space in which participants stood. This was done with the calibration kit included in each system (Qualisys or OptiTrack). The kit consists of a metal frame with several markers fixed to its arms; the frame is placed on the floor in the centre of the desired recording space. A calibration ‘wand’, which is a lighter frame with markers (see Figure 4.6), is moved around the recording space for about 30 seconds, or until the system registers enough data points to create an accurate three-dimensional local coordinate system.

Motion capture markers were attached to participants’ bodies in order to record their movement. For the Championships, only one marker was glued to a Velcro base on the top of the head. For the Headphones/Speakers experiment, in which 20 markers were used per person, a motion capture suit was used. Such suits are made from a Velcro adhesive material that enables secure fastening of markers on points of interest on the body (anatomical landmarks). A suit typically consist of two parts—a jacket and trousers—and various sizes are available. Since placing the markers on the upper part of the body is more complicated, only the jacket was used to attach markers. Instead of using the bottom part of the suit, markers were attached directly to participants’ clothes or skin with double-sided tape, or, depending on what clothes they were wearing, with a band made from Velcro straps (see Figures 4.9, 4.8 and 4.11). The anatomical landmarks are displayed in Figure 4.9.

Static markers were placed in the recording space in order to collect baseline data and account for possible noise (Jensenius et al., 2012). For the Championships, the reference markers were placed on tripods (see Figures 4.1 and 4.2) approximately at a height of participants’ heads. For the Headphones/Speakers experiment, baseline data were collected from reference markers on the floor and the balance board.

Additionally, video recordings were made during each experiment. Four cameras were placed in the corners of the room in order to monitor and document participants’ behaviour (see Figure 4.10).

EMG

While motion capture enables the analysis of the body based on videos recorded from a distance, I thought it would be interesting to also collect data about subtle movement directly from the body. EMG (electromyography) is a method used to measure the electrical activity of muscles. It is useful for analysing muscle activity and motor control (Criswell, 2010). In this experiment, the interest was in the

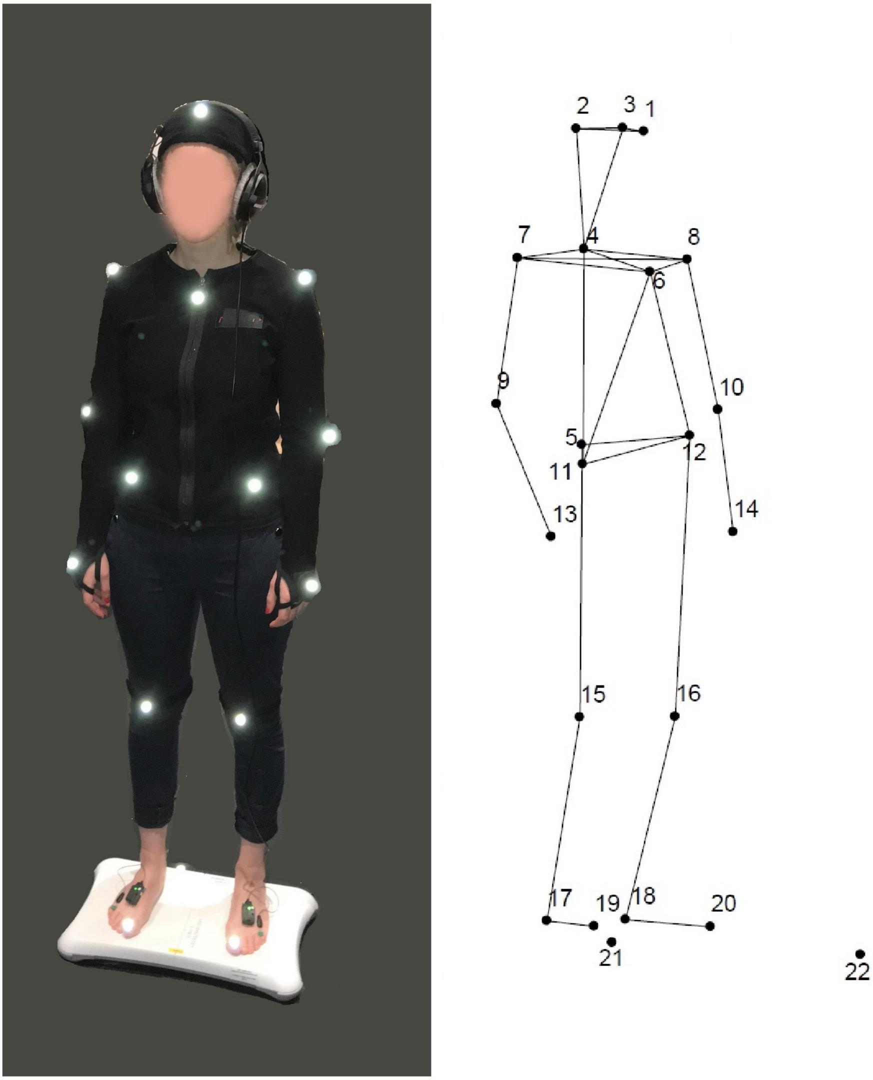

Figure 4.9: Marker configuration for the Headphones/Speakers experiment. Left: motion capture markers placed on the front of the body. The reflections were caused by a camera flash. Right: The location of the markers on anatomical landmarks, including two reference markers (L: left; R: right; F: front and B: back): 1: F head; 2: RB head; 3: LB head; 4: B neck; 5: sacrum; 6: sternum; 7: R shoulder; 8: L shoulder; 9: R elbow; 10: L elbow; 11: R hip; 12: L hip; 13: R wrist; 14: L wrist; 15: R knee; 16: L knee; 17: R heel; 18: L heel; 19: R toe; 20: L toe; 21: reference marker on the Wii board and 22: reference marker on the floor.

Figure 4.10: This figure displays the different ways of viewing the participant during a motion capture recording session. Upper left: Images from four regular cameras placed in the corners of the laboratory displayed using a video mixer. Bottom left: Preview of images from each of the 12 motion capture cameras as displayed in the Qualisys software. Reflections visible to the cameras are displayed as white spots on a black background. Based on such images, it is possible to ensure that cameras register only reflections from the markers (which is ideal) and not other shiny surfaces (which results in artefacts). Right: Representation of the markers, visible as red dots, in the three-dimensional space recreated in the Qualisys software from the images provided by all cameras.

activity of muscles that are associated with head nodding (muscles at the base of the neck), finger movement (muscles in the forearm) and foot tapping (muscles in the dorsal surface of the foot). The device used here was Delsys Trigno (Boston, MA), which is a wireless surface EMG system. This means that the sensors are attached to the surface of the skin (using double-sided tape) instead of being inserted into muscle fibres. Two electrodes were placed on the ventral sides of the forearms (flexor carpi radialis), two on the shoulders (upper trapezius) and two on the feet (extensor digitorum brevis) (see Figure 4.11). The electrodes were placed based on suggestions from SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles, http://www.seniam.org/). EMG signals were recorded at the rate of 2,000 Hz using the Delsys EMGWorks software. As mentioned earlier, the EMG data collected during the Headphones/Speakers experiment have not yet been analysed. A preview of the data is shown in Figure

4.11. The same EMG system was also used to collect data from the audience of an experimental music concert (see Gonzalez-Sanchez et al., 2018, for more information).

Balance Board

Another interesting way to look at small-scale body movement is to observe how people shift their body weight and maintain balance while standing. Several studies collecting balance data have shown changes in postural sway in response to music (Ross et al., 2016b; Coste et al., 2018). For this reason, I used a Nintendo Wii Balance Board in the Headphones/Speakers experiment (Figure 4.12). Participants were asked to stand barefoot on the board during the listening sessions. Although the Wii board is not a professional device for measuring balance, it is a convenient, cost-effective alternative to assess balance (Clark et al., 2010; Chang et al., 2013). Data were recorded using the WiiDataCapture software. Figure 4.12 shows a visualisation of the data stream from the Wii board during one listening session of the Headphones/Speakers experiment.

Breathing Sensor

Among many other physiological processes, music can affect the listener's breathing (Hodges, 2008). As the chest expands with inhalations and contracts with exhalations, breathing can be observed as subtle movement of the body. Jensenius & Bjerkestrand (2011) noticed that breathing patterns create periodic regularities in micromotion data. In the MICRO project, we wanted to further observe the relationship between music-related micromotion and breathing. This motivated us to collect breathing data from participants during the Headphones/Speakers experiment. For this purpose, a FLOW™ sensor developed by the start-up company SweetZpot (Oslo, Norway) was used. The sensor was attached to an elastic belt. When worn, it needed to sit tightly but comfortably on the participant's rib cage, just below the chest (Figure 4.13). The initial idea was to simultaneously collect heart rate data from the same sensor, as the literature shows that the heart rate is also affected by music (Hodges, 2008). However, at that point of time, the heart rate function was not yet available on the FLOW™ sensor. Ultimately, the data from this sensor were not included in the articles presented in this dissertation, but they are currently being analysed and might possibly be published in the near future. For an example of an analysis of data recorded with the FLOW™ sensor, and an evaluation of this and other breathing sensors, see Løberg et al. (2018).

4.3.3 Self-report Measures

In order to better understand the occurrence and nature of music-related movement, self-report data were collected from individual participants. Self-report data collection was done using a pen-and-paper form; participants filled in printed copies of questionnaires. Since collecting these types of data can take a substantial amount of time, it was done in either a brief or an extensive way, depending on the experimental paradigm. The Championship paradigm allowed for spending less time on questionnaire data collection than the Headphones/Speakers paradigm, which had individual listening sessions. Data on participants' experience of the process were collected following all experiments, along with data on participants' age, gender and music-related habits and preferences (see Section 4.3.3). In some experiments, music-related behaviours were examined in more detail (see Section 4.3.3), and personality and empathy traits were measured (see Section 4.3.3).

Selection

There are multiple tools available to examine individual differences. Well-researched concepts such as personality or empathy can be measured with various standardised psychometric questionnaires. In such cases, the main challenge is choosing the most suitable test for a given population and experimental paradigm. To select appropriate questionnaires, I have tested many of them on myself, fellow researchers and a group of students.

In general, there are several important things to consider while choosing between existing questionnaires:

1. Time limit. Both long questionnaires and a large number of questionnaires could overwhelm participants, making them lose focus, or get tired or bored. These issues, in turn, could impact the quality of the collected data. Moreover, including a long questionnaire may discourage participants from taking part in the study, as it would require a substantial time investment. A balance needs to be found between measuring concepts in sufficient detail and making sure that data collection is not too long or troublesome.

2. Population. Some questionnaires are created with a specific target group in mind, such as children, patients, or people with certain types of expertise. It is important to check for whom a given questionnaire was designed, and whether it is appropriate for the population one wants to examine. This information is usually reported in the original research article that introduced and described the design of a questionnaire tool. Moreover, even if the questionnaire was not designed for any specific population, it is still worth considering whether the population it was tested on matches the current population. Some items in questionnaires can be context-specific. For example, questionnaires that test intelligence often include items that are culture-specific and require knowledge that a person who is not immersed in the given culture is unlikely to possess.

3. Language. Psychometric tools, especially if they are being used for professional diagnosis, should not be translated by researchers independently. Small changes to wording can change the original meaning, thus making questionnaire items deviate from their original purpose.

Therefore, the results and their interpretations can be skewed, and comparing the results of various studies may be difficult. If there is no official version of a questionnaire in a given language, other questionnaires used to measure the same concept (i.e., intelligence or personality) should be considered. If the researchers decide to translate a questionnaire because of a lack of other options, it is crucial to include the translated version in the research report. Another important thing to consider is the language proficiency of the participants. It is best to choose questionnaires that are transparent in their use of words, especially if participants are not native speakers of a given language, but are sufficiently skilled to complete the questionnaire. Idiomatic expressions should be avoided, as participants might misunderstand them.

4. Priming bias. Priming occurs when a preceding event affects the current event; in this case, filling in a specific questionnaire affects performance in the following tasks. Whether these following tasks are other questionnaires or experimental procedures, it is important to consider how the content of the questionnaire connects with the following tasks. The questionnaire might reveal what the researchers are interested in, which might affect the collection of data. Moreover, after completing a questionnaire, participants might feel the need to act in a way that matches their answers (e.g., collaborate well with another participant in a joint task, if the questionnaire contains items about helping others). In sum, the order of filling in questionnaires, and the overall sequence of questionnaires and other experimental tasks, matters.

In the experiments presented in this dissertation, participants had mixed linguistic backgrounds, including Norwegian and several others. All the chosen and designed questionnaires were in English, except for the questionnaire included in the Championship in 2012, which was conducted in Norwegian.

Before including specific questionnaires, I conducted a pilot on a group of Norwegians students. All the questionnaires that were considered for use were distributed in printed form, and after the students filled them in, each questionnaire was discussed with the students. Based on their feedback, some questionnaires appeared to be problematic, and were, therefore, not included in the experiments. The excluded questionnaires will be briefly discussed in the following paragraphs, after presenting the questionnaires that were used.

For the experiments, the following questionnaires created by other authors were used:

1. Barcelona Music Reward Questionnaire (Mas-Herrero et al., 2013)
2. Short Test of Music Preferences (Rentfrow & Gosling, 2003)
3. Beat Alignment Test questionnaire (Iversen & Patel, 2008)
4. Big Five Inventory (John & Srivastava, 1999)

5. Interpersonal Reactivity Index (Davis, 1980)

We also created a customised questionnaire for each experiment. These tools, as well as the process of selecting or creating them, are described in detail below. They were grouped into three categories: music-related, psychometric, and self-made questionnaires.

Music-related Questionnaires

These questionnaires were used to measure the various music-related characteristics of participants, such as their music preferences, habits and experiences. All of the questionnaires listed here were used for the Headphones/Speakers experiment. The BMRQ and BAT questionnaires were also used during MusicLabs (Gonzalez-Sanchez et al., 2018).

As mentioned earlier, there were several music-related questionnaires that were considered but ultimately not used for the studies presented in this dissertation. However, they are also listed here, and the decision to not use them is explained. These tools can still be useful for studies on body movement and other bodily responses to music.

Barcelona Music Reward Questionnaire (BMRQ) This 20-item questionnaire was designed by Mas-Herrero et al. (2013) and is available in Spanish and English. It measures the reward experiences that a person typically gets from music. It comprises five subscales: Emotional Evocation (EE; e.g., *I get emotional listening to certain pieces of music*; *I sometimes feel chills when I hear a melody that I like*), Sensory-Motor (SM; e.g., *Music often makes me dance*; *I can't help humming or singing along to music that I like*), Mood Regulation (MR; e.g., *Music calms and relaxes me*; *Music comforts me*), Musical Seeking (MS; e.g., *I'm always looking for new music*; *I spend quite a bit of money on music and related items*) and Social Reward (SR; e.g., *I like to sing or play an instrument with other people*; *At a concert I feel connected to the performers and the audience*). The answers are provided on a five-point scale with options ranging from *Completely disagree* to *Completely agree.* Two of the items are reverse scored: *I don't like to dance, not even with music I like* (SM) and *In my free time I hardly listen to music* (MS). Naturally, for the purpose of studying music-induced movement, the Sensory-Motor scale seemed particularly relevant. However, the other scales were also included in the experiment, in order to evaluate whether and how different styles of engagement with music correspond to the amount of observed movement.

Short Test of Music Preferences (STOMP) This questionnaire was created by Rentfrow & Gosling (2003) and exists as an original 14-item version (STOMP) and as a revised and extended 23-item version (STOMP-R). In this dissertation, the 14-item version was used. Each questionnaire item is a name of a music genre (*Classical, Blues, Country, Dance/Electronica, Folk, Rap/Hip-hop, Soul/Funk, Religious, Alternative, Jazz, Rock, Pop, Heavy Metal and Soundtracks/Theme* *songs*). They are grouped into four categories: *Reflective & Complex*, *Intense & Rebellious*, *Upbeat & Conventional* and *Energetic & Rhythmic*. Participants are asked to indicate their basic preference level for each of the 14 genres, using a seven-point scale ranging from *Strongly dislike* to *Strongly like*. The decision to use STOMP instead of STOMP-R was motivated not only by the fact that it was shorter, but also because STOMP-R contained several problematic items. When the questionnaire was tested on a group of Norwegian students, items such as *Bluegrass*, *International/Foreign* and *Oldies* were reported as being confusing. Some students did not know about bluegrass music and the 'international' music category seemed ambiguous. It is clear that STOMP and STOMP-R were designed and tested on American populations, and reflect music genres that are most common in that culture. In fact, even in the shorter version of the test, students raised concerns about two items—*Alternative* and *Dance/Electronica*. As they rightly pointed out, both the alternative and electronica genres are particularly broad, so it was hard for them to indicate their preferences with regards these genres. On the other hand, naming the questionnaire item *Dance/Electronica* seemed to straightforwardly indicate that the authors were interested in preferences with regards EDM.

Beat Alignment Test Questionnaire (BAT) This questionnaire was developed for use at the end of the Beat Alignment Test (Iversen & Patel, 2008). The test comprises two tapping tasks and one listening task, which were designed to assess beat processing abilities in the general population. It uses real music samples to measure how well participants can synchronise their tapping to the beat, and how well they perceive regularities in the beat. BAT was one of the measures that was considered for the Headphones/Speakers experiment. However, the whole test takes about half an hour to complete, and since the experiment was already quite long, the tapping and listening tasks were ultimately not included. Still, the BAT questionnaire (Iversen & Patel, 2008), developed to collect data on participants' musical and movement/physical backgrounds, appeared to be concise and a good fit for the Headphones/Speakers experiment, as well as for some of the Championships and MusicLabs. It starts with questions about gender, age and potential hearing problems. Following this, there are questions about frequency of listening to music, dancing and practising sports or other physical activities (from *Never* to *Very often*). There are also open questions about preferred genres of music, dance styles and sports/activities. All the questions above overlap with some other items from the custom-made questionnaires, so they were not used, apart from in one MusicLab, where the full questionnaire was used in its original form (Gonzalez-Sanchez et al., 2018). Other questions from the BAT questionnaire, and those that were used in several custom-made questionnaires, included *How would you rate your overall sense of rhythm compared to the general population?* (*Poor/Below average/Average/Good/Excellent*) and *In general, how would you rate your physical coordination?* (*Clumsy/Below average/Average/Good/Excellent*). There were also more detailed questions about musical training, opened with *Do you* *have any musical training?*. Participants who answered yes were first asked *Please list what instruments, including voice, you have studied (and for how long)* (open question), and then, *Are you still playing an instrument?*. For those who said yes, the next question was *Which instrument, and how many hours per week do you practice?*. For those who said no, the next question was *How long ago did you stop?*. These were also open questions. A critical look at this questionnaire can be found in Limitations (Section 6.3).

Musical Entrainment Questionnaire (MEQ; not used) A promising questionnaire for the Championship and Headphones/Speakers experiments was the Musical Entrainment Questionnaire (MEQ) designed by Labbe & Grandjean (2014). It is a 12-item questionnaire that comprises two subscales: Visceral Entrainment, describing sensations of internal bodily entrainment, and Motor Entrainment, describing an inclination to move to the beat. The second scale seemed particularly useful to compare whether movement observed with motion capture would correspond with a self-assessed tendency to move to music. This questionnaire was originally created in French, but the authors have provided an English translation (Labbe & Grandjean, 2014). The questionnaire was designed to evaluate responses to music samples during an experiment, and not listening habits and responses to music in general. In the original version of the questionnaire, every item started with *To what extent did you...*, and was followed by 12 different responses: *feel physically stimulated*, *feel like dancing*, *feel entrained/driven*, *feel like moving*, *feel physically excited*, *feel bodily agitated*, etc. We have changed *To what extent did you...* to *When you listen to music you like, to what extent do you normally...* and *When you listen to music generally, to what extent do you normally...*, each followed by the 12 items.

When the questionnaire was tested on a sample of Norwegian students, several of them reported that it was confusing and difficult to relate to daily life. Even though we proposed two hypothetical situations (listening to music they like or to music generally), the students pointed out that their answers would depend on the situation and context in which they were listening to music; for example, whether they had chosen the music themselves, or what kind of music it was from among all the music they like. Moreover, individual items of the questionnaire seemed fairly similar to each other, which was problematic for both the students and the experimenters, particularly when the latter had to interpret the collected data. Students found several items difficult to understand (e.g., *feel entrained/driven* and *feel your own bodily rhythms change*). Last but not least, the suggested answering scale, from 0 to 100, did not correspond well with scales in the other questionnaires.

Taking all these problems into consideration, we decided that the Sensory-Motor scale from the BMRQ, although less robust, was a better measure of the tendency to spontaneously move to music. However, the MEQ seems a useful tool to consider for other music listening studies, especially if they pertain to specific music material. Indeed, we considered asking participants to fill in the questionnaire for each stimuli track in the Headphones/Speakers experiment, but that would have taken a substantial amount of time, and some of the problems listed above would have come up.

Ollen Musical Sophistication Index (OMSI; not used) The Ollen Musical Sophistication Index (OMSI) developed by Ollen (2006) was considered to measure musical expertise. This questionnaire comprises only 10 questions. However, several questions require long and detailed answers, and many questions have a robust list of answers to choose from. While this questionnaire seemed to be an optimal tool to assess musical expertise, other questionnaires were ultimately prioritised for the Headphones/Speakers experiment. For the Championships, the standard questionnaire is approximately the duration of the OMSI, so completing both would require double the amount of time. As an alternative, selected questions from the compact BAT questionnaire were used to assess the level of musical training and practice experience. Retrospectively, this might have been not the best decision, and its consequences will be discussed in the Limitations section (see Section 6.3). In experiments with a pressing time limit, perhaps just the last question from the OMSI would be a simple and sufficient measure to distinguish between less and more musically experienced participants. The question is *Which title best describes you?*. The answer includes the following items: *Nonmusician*, *Music-loving nonmusician*, *Amateur musician*, *Serious amateur musician*, *Semiprofessional musician* and *Professional musician*. This question was used in the 2019 edition of the Championship of Standstill.

Psychometric Questionnaires

These questionnaires collect information about participants that relate to their personality traits. Both the BFI and IRI were used for the Headphones/Speakers experiment. The IRI was also used in the 2019 edition of the Championship of Standstill. As in the preceding section, after presenting these questionnaires, I will list two psychometric questionnaires that I considered, but did not use, for the experiments described in this dissertation. Still, the concepts that they measure are definitely worth considering for future studies.

Big Five Inventory (BFI) There are multiple tools available to measure personality, often based on a popular five-factor personality model called the ‘Big Five’. This model was developed over decades of research on personality (John & Srivastava, 1999) and distinguishes five main factors in personality: Openness to Experience, Conscientiousness, Extraversion, Agreeableness and Neuroticism. Taking the first letters of these factors, it is also sometimes referred to as the OCEAN model. Some of the questionnaires developed for studying Big Five traits are long and detailed; for example, the NEO Personality Inventory developed by Costa & McCrae (1992) comprises 240 items. Some have just 10, or even 5 items (Gosling et al., 2003). One of the most popular tools is the 44-item Big Five Inventory (BFI) created by John & Srivastava (1999). In this questionnaire, traits like Extraversion (an enthusiastic approach to social activities, assertiveness and positive emotionality) and Neuroticism (a tendency to feel anxious, nervous, sad and tense) are each measured with eight items. Agreeableness (a prosocial orientation, altruistic behaviour, modesty and trust) and Conscientiousness (a tendency for well-thought, organised behaviour, impulse control and following norms and rules) are each measured with nine items. Openness to Experience (as opposed to closed-mindedness, characterised by a deep, complex and original experiential and mental life) is measured with 10 items. Each item starts with *I see myself as someone who...* and is followed by a statement to which participants respond on a five-point scale, ranging from *Disagree strongly* to *Agree strongly.* Some of the items are reverse scored. For example, one of the items for Extraversion is *I see myself as someone who is full of energy*, and one of the reverse scored items is *I see myself as someone who is reserved.* Other exemplary items are *I see myself as someone who can be tense* (Neuroticism), *I see myself as someone who is helpful and unselfish with others* (Agreeableness), *I see myself as someone who does a thorough job* (Conscientiousness) and *I see myself as someone who is curious about many different things* (Openness to Experience). The scores for each trait are calculated as the mean of the values of all the items assigned to this trait.

Interpersonal Reactivity Index (IRI) As with personality, there are various ways in which empathy can be measured. The components of empathy differ between models, and there is less agreement about the structure of this trait. Some researchers argue that empathy is not a fixed characteristic of an individual, but rather a set of skills, or a tendency towards certain types of behaviours depending on the circumstances (Clarke et al., 2015). However, there are several measures available for the psychometric evaluation of the types and levels of empathy, such as the Interpersonal Reactivity Index (Davis, 1980), Empathy Quotient (Baron-Cohen & Wheelwright, 2004), Toronto Empathy Questionnaire (Spreng et al., 2009), Questionnaire Measure of Emotional Empathy (Mehrabian & Epstein, 1972) and The Empathy Scale (Hogan, 1969). Among studies on music and movement, the IRI (Carlson et al., 2016) and Empathy Quotient (Carlson et al., 2019; Bamford et al., 2016; Bamford & Davidson, 2017; Hartmann et al., 2019) seem to be the most popular. The Empathy Quotient (EQ) measures the cognitive and affective aspects of empathy, and the score encapsulates empathy as a single trait. IRI comprises four subscales: Perspective Taking (PT; the tendency to spontaneously adopt the psychological point of view of others), Empathic Concern (EC; 'other-oriented' feelings of sympathy and concern for unfortunate people), Personal Distress (PD; 'self-oriented' feelings of personal anxiety and unease in tense interpersonal settings) and Fantasy (FS; the tendency to transpose imaginatively into the feelings and actions of fictitious characters in books, movies and plays). Empathy is defined as the 'reactions of one individual to the observed experiences of another' (Davis, 1983, p.113).

Each scale of the IRI comprises 7 items, for a total of 28 items. The answers are provided on a four-point scale ranging from *Does not describe me well* to *Describes me very well.* Some exemplary items are *I try to look at everybody's side of a disagreement before I make a decision* (PT), *When I see someone being* *taken advantage of, I feel kind of protective towards them* (EC), *I tend to lose control during emergencies* (PD) and *I really get involved with the feelings of the characters in a novel* (FS). Some of the items are reverse scored; for example, *Sometimes I don't feel very sorry for other people when they are having problems* (EC).

Behavioural Inhibition System and Behavioural Activation System Scales (BIS/BAS; not used) One questionnaire that was considered but not used was the BIS/BAS Scales by Carver & White (1994). The name BIS/BAS refers to the behavioural inhibition system and behavioural activation system. These are two opposite motivational systems regulated by physiological processes that control responses to environment cues (aversive or appetitive). Activity in the inhibitory system causes the person to withdraw from movement towards goals, whereas activity in the activation system causes a person to begin, or to increase, movement towards goals (Carver & White, 1994). The questionnaire comprises 24 questions which measure the sensitivity of both of these systems in a given person. The idea was to use this tool to see whether these systems are connected to spontaneous movement responses to music. However, when tested on a group of Norwegian students, the questionnaire appeared to be troublesome. It contains items such as *When I go after something I use a 'no holds barred' approach*, *If I think something unpleasant is going to happen I usually get pretty 'worked up'*, *I often act on the spur of the moment*, or *When I want something I usually go all-out to get it.* These idiomatic expressions were reported as confusing by the Norwegian students. Therefore, the questionnaire was not used in the experiments.

Barratt Impulsiveness Scale (BIS11; not used) Another questionnaire that was considered but was then rejected was the revised Barratt Impulsiveness Scale (BIS11) by Patton et al. (1995). This is a 30-item questionnaire comprising of three subscales: Attentional Impulsiveness, Motor Impulsiveness and Nonplanning Impulsiveness. Although a promising tool for evaluating whether impulsiveness connects with unintentional movement in the Championship of Standstill studies, we rejected this questionnaire, as we did the BIS/BAS, because there were to many idioms and confusing items. The test group of Norwegian students reported having problems with items such as *I am happy-go-lucky*, *I 'squirm' at plays or lectures* and *I often have extraneous thoughts when thinking.* Moreover, the four-item scale (from *Rarely/Never* to *Almost always/Always*) was different from the answering scales in the set of questionnaires we used, which was somewhat confusing. One could argue that the scales could have been standardised across questionnaires, but changing scales in existing psychometric questionnaires is not advisable.

Self-made Questionnaires

Throughout the different experiments, several custom-made questionnaires were used. As explained earlier, the questionnaires for the Championships of

Standstill tended to be much shorter than they were for the Headphones/Speakers experiment (the reasons for this can be found in Section 4.2). These questionnaires will be discussed chronologically, to illustrate their gradual development.

Championship of Standstill The first questionnaire used for the Championships of Standstill in 2012 and 2015 (i.e., before the MICRO project was started) consisted of a fairly short set of items and was designed in Norwegian. The questionnaire items, translated here into English, can be divided into two categories:

1. Demographics and Habits
    - Age
    - Gender
    - How many hours per week do you usually listen to music?
    - How many hours per week do you usually play/produce/compose music?
    - How many hours per week do you usually dance (both as an exercise and socially)?
    - How many hours per week do you usually exercise (sport activities other than dance)?
2. About the Experiment
    - Did you find it tiresome?
    - Did you feel that you were moving (compared to standing completely still)?
    - Did you feel you were moving more to music than in silence?
    - Did you close your eyes?
    - Did you lock your knees?

The purpose was to understand whether people with certain habits are better at standing still in silence and in music, how different strategies of standing impact the amount of movement, and whether participants' perception of their own movement matches the recorded motion capture data.

For the questions from the 'About the experiment' section, answers were provided on a five-point scale. Only the extremes of the scale had captions: from *Not really* (*Ikke særlig)* to *Yes, a lot* (*Ja, veldig)* for the question about tiredness, and from *Not at all* (*Ingenting*) to *A lot* (*Masse*) for the two questions about the person's own perceived movement. The questions about eyes and knees had three answers to choose from: *Yes/No/Both* (*Ja/Nei/Både og*).

Over the years, the above set of questions was used in the many editions of Championship of Standstill. The purpose was to compare data across different editions of the experiment. However, some changes to the above set of questions were implemented.

In 2017, two additional questions were included: *How did you feel prior to the experiment?*, followed by two five-point scales with *Tired* to *Wakeful* as the extremes on one, and *Relaxed* to *Tense* as the extremes on the second. There were also some changes to the wording; e.g., *Did you feel that you were moving (compared to standing completely still)?* was changed to *How much did you feel that you moved?*. Familiarity with the music recordings was noted (participants ticked a box if they had heard a particular recording before).

In 2018, three of the BAT questionnaire items were used: *How would you rate your overall sense of rhythm compared to the general population?*, *In general, how would you rate your physical coordination?* and *Do you have any musical training?* (see Section 4.3.3 for a detailed description of these questions). Two additional questions were formulated, *Do you like to dance?* (five-point scale ranging from *Definitely not* to *Definitely yes*), and a question about familiarity with music stimuli was added (*Have you heard before any of the presented music records?*).

In 2019, only one question from the BAT questionnaire was added: *How would you rate your overall sense of rhythm compared to the general population?*. The same question about liking to dance appeared, as in 2018: (*Do you like to dance?*). The last item from the OMSI was used to measure musicianship status: *Which title best describes you?* (*Nonmusician/Music-loving nonmusician/Amateur musician/Serious amateur musician/Semiprofessional musician/Professional musician*). In this edition, participants also filled in a complete version of the IRI.

Each questionnaire ended with a section in which participants were encouraged to write freely about their experience. While these comments were not included in the analysis, they informed us of the participants' experience with the experiment and aided the design of future studies. In some cases, they also helped us understand events in the motion capture data and/or make decisions regarding removing a given participant from the analysis.

Headphones/Speakers The Headphones/Speakers experiment was much more robust in its use of questionnaires. Apart from the BMRQ, STOMP, BFI and IRI questionnaires, several custom-made questionnaires were used. Some of their items overlap with those of the Championship of Standstill questionnaires. Below, the stages of filling in the questionnaires in the Headphones/Speakers experiment will be explained:

1. Immediately after each of the two listening sessions, participants filled in a short questionnaire about the session they had just completed; the questionnaire contained questions about tiredness, knee position, closing of eyes, focus on breathing, perceived movement and perceived loudness.

2. Between listening sessions, participants filled in the BFI and IRI.

3. After the second listening session, participants filled in a longer questionnaire that comprised a few categories of questions: demographics and habits (analogous to questions in the Championships), several BAT questionnaire items, questions about the experiment, and habits and preferences associated with using headphones and speakers.
4. After this questionnaire, participants filled in the BMRQ and STOMP.
5. After STOMP, two open-ended questions were added in which participants were asked to describe the features of the music that they preferred and disliked.
6. Finally, participants were asked to evaluate how much they liked listening to the records presented during the experiment. An excerpt of each track was played, and then they had to give an answer on a scale ranging from 1 (Dislike strongly) to 7 (Like strongly), just like in STOMP. They were also asked if they were familiar with any of the music records before participating in the experiment.

After all questionnaires were completed, the participants were asked about their perceived differences between headphones and speakers listening in the experiment and in everyday life. This was not considered a part of the standard data collection, but more an opportunity for participants to express their thoughts, and for the researcher to understand better how people experience the two playback methods. There are two main reasons why a systematic analysis of these data was not possible. First, it was not a properly designed research interview. The questions were loosely formulated and varied slightly from participant to participant, depending on the flow of the conversation. The answers were not recorded but were written down immediately after the participant left the room. Second, the questions were asked of only 27 out of the 42 participants, and the level of detail in their answers varied remarkably. Insights from these conversations with participants will be considered in the Discussion.

4.4 Data Analyses

In this section, the methodology of data analysis will be discussed in the same order as in Section 4.3: starting with sound stimuli, through body movement and then self-report measures. At the end of this section, the statistical analyses for all types of data will be discussed together, since they were analysed in conjunction.

4.4.1 Sound Stimuli

The stimuli were analysed according to their sound features. This was done using the Music Information Retrieval (MIR) toolbox for Matlab (Lartillot & Toiviainen, 2007). This tool enables the extraction of various features from any sound file. In the five papers, the focus was on pulse clarity (Paper II), event density (Paper III), tempo (Paper II and Paper V) and loudness and brightness (Paper II). In Paper V, the tempo was predetermined in the stimuli design, so it did not need to be extracted with MIR (just as with other self-made tracks used in Paper III and Paper IV). Details regarding the extraction of sound features can be found in the papers. Extracting these features allowed for further investigation of the qualities of music that can be linked to spontaneous body movement.

Based on the MIR results, there were two types of analyses. In the first one, the extracted sound features were cross-correlated with events in the movement data (Paper II). In the second one, quantifying features enabled dividing the stimuli into groups that were characterised by a high or low saturation of these features. This was the case in Paper III; based on event density, the stimuli were divided into high and low musical complexity.

4.4.2 Body Movement Data

Motion capture data were recorded and pre-processed in Qualisys Track Manager (QTM), and further analysis was done in Matlab using the MoCap Toolbox (Burger & Toiviainen, 2013). This will be explained in more detail in the following sections.

Pre-processing

For each individual recording, pre-processing of data in QTM started with assigning labels to each marker (see Figure 4.9). For example, the markers on the heels were labelled RHEEL (right heel), LHEEL (left heel), and those on the hips were labelled RHIP (right hip) and LHIP (left hip). This facilitated identifying markers at each frame and pre-assessing the quality of the recording. Then, gaps in the data and misidentified markers were manually corrected. Audiovisual material from the four video cameras and notes from the experiment were used for reference. Pre-processed data were then exported as .TSV files and imported into Matlab for further analysis.

Feature Extraction

The main movement feature analysed in all the studies was the Quantity of Motion (QoM). This was computed as the sum of all the position differences of consecutive samples of a motion capture marker. The resulting QoM was measured in millimeters per second (mm/s). This measure was thought of as representative of the amount of movement over time. QoM was computed both for each instance of time, and as an average over longer time segments (for example, for movement during one sound stimuli, or a whole listening session).

As explained in Section 4.2, only head movement was analysed in the Championships because of technical challenges associated with measuring the movement of other body parts in a group setting. In the Headphones/Speakers study, the experiment design allowed for the analysis of different relevant body parts. With a 20-marker full-body set-up, many different approaches to extracting movement features were possible. In the end, the decision was to focus on the head (Head), the center of mass (CoM) and a global measure of whole body movement (Body).

The Head measure enabled a comparison with the Championships data, but it was also chosen because moving the head is one of the most typical responses to music, and it has been measured in some relevant studies (Hurley et al., 2014; Kilchenmann & Senn, 2015). The interest in CoM came from studies on the effect of music on human posture and balance (Ross et al., 2016b; Coste et al., 2018). The decision to average data from all markers, creating the Body measure, was made based on the general interest in any type of movement in any body part.

Apart from the Head and CoM movement, it could have been interesting to look at, for example, movement of the shoulders, arms, hips and knees. However, looking at individual parts of the body would also have meant creating many more variables, which would have further complicated the data analyses in this already complex experimental design (Papers III and IV). In fact, in Paper IV, we decided to only use the Body measure, as there were many other variables to include in the analysis. There are, indeed, many more possible approaches to this set of motion capture data that should be further explored.

4.4.3 Self-report Data

Data from all the questionnaires were first transcribed into Excel files and then exported to SPSS IBM Statistics. The comments from participants, as well as notes from the investigator about a given session, were transcribed into the Excel database and kept for reference.

4.4.4 Statistical Analyses

For each study, a database consisting of movement and self-report data was compiled in Excel. The database was then exported into SPSS IBM Statistics, where it was prepared for subsequent analyses by labelling data, creating filters and computing new variables. Before conducting any statistical tests, the variables of interest for a given study were explored using descriptive statistics. In some instances, outliers were eliminated based on the standardised scores for a given variable. The statistical analysis differed slightly between the two paradigms, as described below.

Championships of Standstill

Statistical comparisons of movement data between music and silence segments were computed using paired sample t-tests. The differences in movement between genders were assessed using independent samples t-tests. Additionally, Pearson correlations between movement and several questionnaire items (e.g., age and physical activity) were computed. In Paper II, the correspondences between movement and extracted music features (pulse clarity, loudness and brightness) were measured using cross-correlations between these two types of data. A linear mixed effects model was employed to further analyse the effects of music on movement and interactions between groups of participants and between stimuli. In Gonzalez-Sanchez et al. (2019), we explored a different approach to studying the relationships between movement and music. Fluctuations in head movement were measured in a detrended fluctuation analysis (DFA) (Feder, 2013). This paper is not included as part of this thesis.

Headphones/Speakers

Two different approaches to analysing data from this experiment were applied in Paper III and Paper IV. In Paper III, the main focus was on comparing movement between the headphones and speakers listening sessions. At the same time, the interest was in seeing whether the complexity of the stimuli corresponded with movement in these two listening scenarios. Moreover, three different movement measures were tested. Combining all these elements in one analysis was done using a repeated measures ANOVA, where playback methods, event density and movement measures were within-subject factors. In this way it was possible to see if there were significant differences within the factors and any interactions between them. The questionnaire data were mainly analysed using Spearman rather than Pearson correlations because some of the questionnaire scores were not normally distributed. In Paper IV, the interest was in understanding which of the personal characteristics and habits could explain the amount of spontaneous movement. This was done using regression analyses—various variables from the questionnaires were analysed to determine the best movement predictors. Separate regression models were built for movement to EDM music, movement to the beat track and the self-reported tendency to move. Additionally, independent samples t-tests were performed to compute differences between male and female participants, and those between musically trained and non-trained participants, for all the three dependent variables.

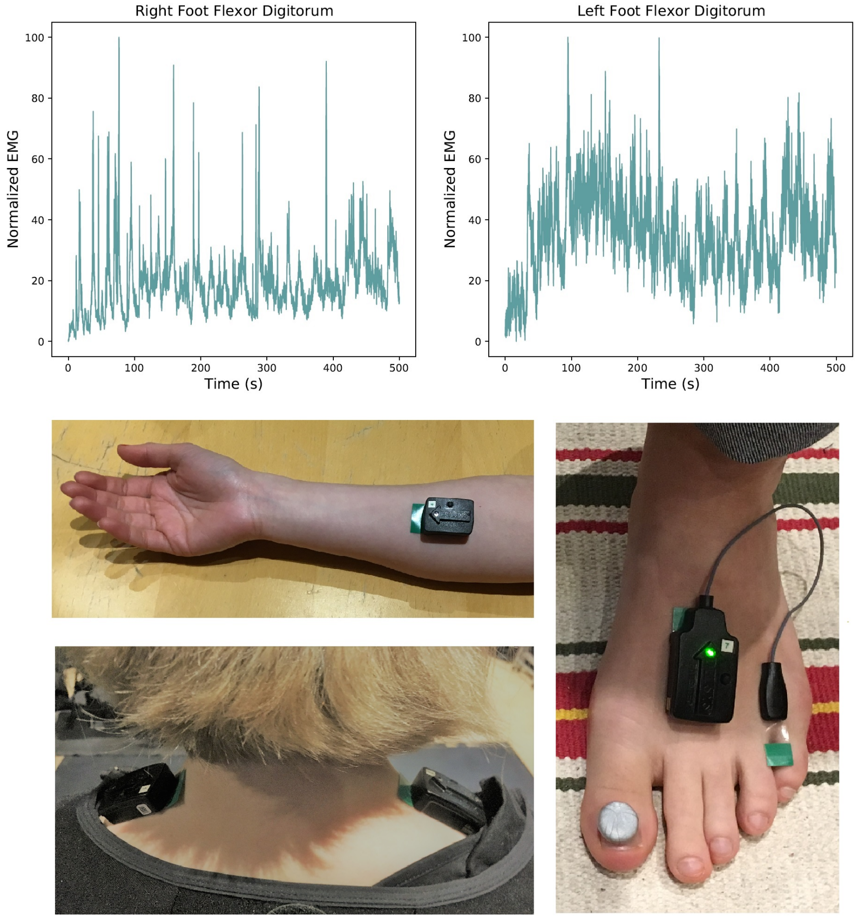

Figure 4.11: An exemplary plot of EMG data from the Headphones/Speakers experiment. The plot shows shifts in muscular activity in the right and left feet throughout a listening session. Photos show the placement of the sensors on each forearm, shoulder and foot.

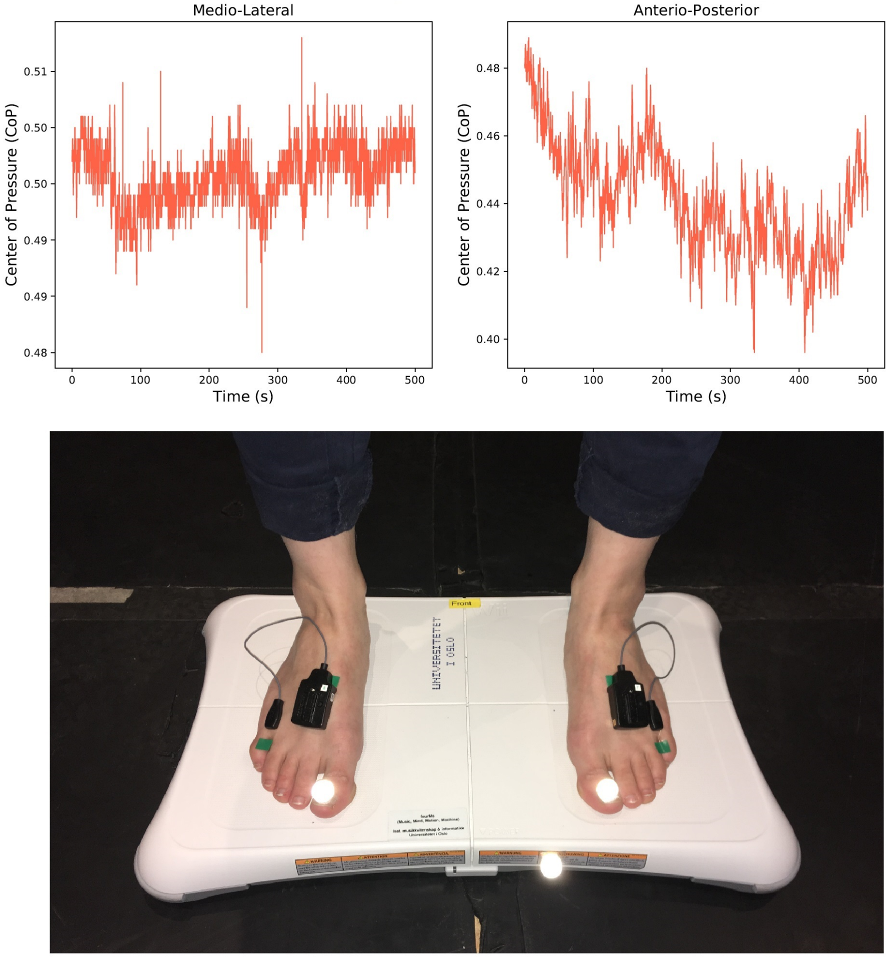

Figure 4.12: An exemplary data plot from the Wii balance board used in the Headphones/Speakers experiment. The plot shows shifts in weight distribution from side to side (medio-lateral) and from toes to heels (anterio-posterior) throughout a listening session. The photograph shows one participant's feet, equipped with EMG electrodes and motion capture markers, on the balance board. The participant is standing facing the opposite direction that they would during the experiment to show the location of the reference marker on the edge of the balance board. The reflections from the markers are due to the camera flash.

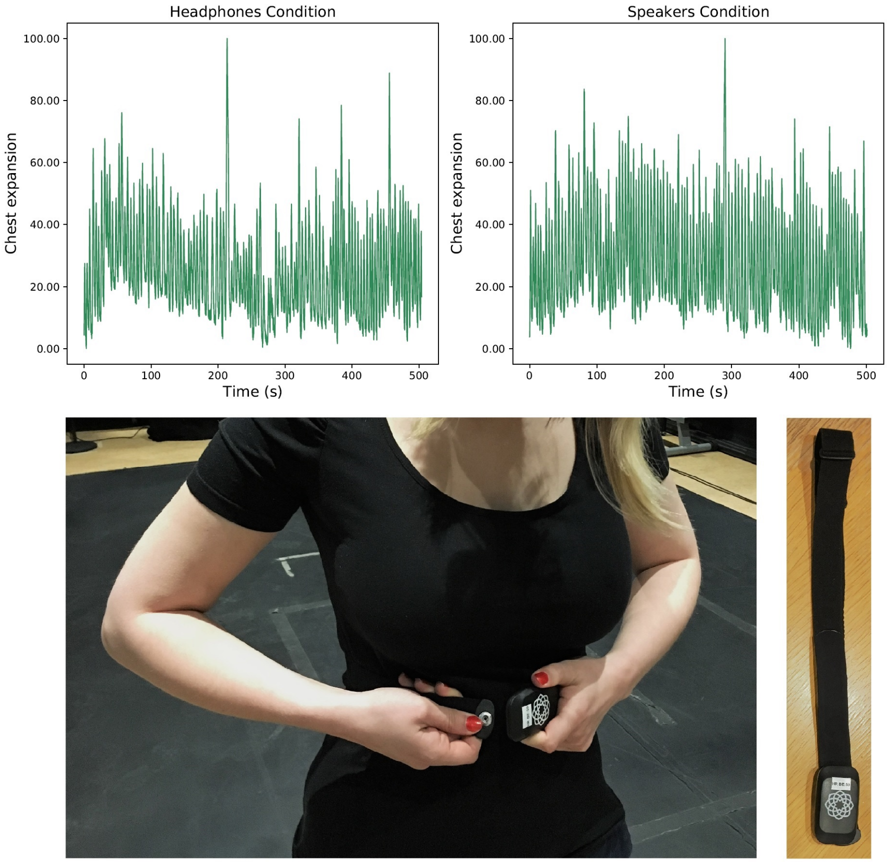

Figure 4.13: An exemplary plot of data from the FLOW™ breathing sensor in the Headphones/Speakers experiment. The plot shows a comparison of chest expansion while breathing during the headphones and speakers listening conditions. The photographs show the sensor attached to an elastic belt and a participant demonstrating where to place the sensor.

Chapter 5

Research Summary

5.1 Introduction

The experimental research described in this thesis was performed as a part of the MICRO (Human Bodily Micromotion in Music Perception and Interaction) Project. The selected papers (Papers I–V) that resulted from this research are presented in chronological order in the dissertation, and will be described in more detail in this chapter. Therefore, it is possible to follow the evolution of the research paradigms, as they transformed based on the findings from the previous experiments.

Some of the papers (Papers A–D) that I have worked on as a co-author are not included in this thesis. However, they will be briefly summarised in this chapter, as they give a fuller picture of the MICRO project and place some of my work within a larger context. These papers are presented in Section 5.3 in order of relevance to the experimental work described in this thesis. As such, Paper A connects to the rest of the papers as it is based on data from one of the Championships of Standstill and was considered for inclusion in this thesis. Paper B, although presenting a new, exploratory research paradigm, still remains within the domain of spontaneous bodily responses to music. Papers C and D, however, are substantially different from the other papers, as they explore new ways of creating (and interacting with) musical instruments.

5.2 Papers

5.2.1 Paper I

Reference: Jensenius, A. R., Zelechowska, A., & Gonzalez Sanchez, V. E. (2017). The musical influence on people's micromotion when standing still in groups. In *Proceedings of the 14th Sound and Music Computing Conference* (pp. 195-200). Aalto University.

Abstract

The paper presents results from an experiment in which 91 subjects stood still on the floor for 6 minutes, with the first 3 minutes in silence, followed by 3 minutes with music. The head motion of the subjects was captured using an infra-red optical system. The results show that the average quantity of motion of standstill is 6.5 mm/s, and that the subjects moved more when listening to music (6.6 mm/s) than when standing still in silence (6.3 mm/s). This result confirms the belief that music induces motion, even when people try to stand still.

Discussion

This paper is based on a data set from the first edition of the Championship of Standstill, which took place in 2012. The main aim of that experiment—and of all Championships of Standstill—was to see whether music indeed *moves us* (or *makes us move*). Such claims often appear both in scientific literature and everyday language, but so far there has been no empirical evidence showing the immediate effect of music on spontaneous body movement (i.e., movement that occurs without planning, resulting from an impulse). Most experiments on music-related movement have involved asking people to move to music, and although these studies have uncovered interesting relationships between music and movement, they have not proven that music *induces* movement.

The simplest approach to testing this assumption was to see whether people would move more to music than in silence if they tried to stand as still as possible. A good opportunity to conduct such a test on a large group of people was during the University of Oslo's annual Open Day. Groups of people visiting the Department of Musicology were invited into the motion capture laboratory to participate in a short research experiment. In this way, three goals were accomplished: collecting data, advertising the Department of Musicology, and spreading knowledge about motion capture technology. The experiment was designed in the form of a competition, where the person who stood the stillest could win a 1,000 NOK gift voucher. This not only motivated participants to take part, but increased their motivation to obey the experiment instruction to try to remain as still as possible. In this first edition, 100 people participated.

As hypothesised, this experiment confirmed the 'movement-inducing' properties of music, showing that, on average, people move significantly more to music than in silence when they are trying to stand still. However, in this edition of the Championship, people spent the first half of the experiment standing in silence, and the second half listening to music. This led to the critique that the increased amount of movement in the second part of the experiment was not due to the effect of music, but due to a growing tiredness from standing. Moreover, the music samples used in this study—although representing a variety of genres—did not allow for a proper comparison of the types of music, as they were not presented in a randomised order, and they varied in duration. This feedback was important for revising the experiment paradigm for later Championships.

5.2.2 Paper II

Reference: Gonzalez-Sanchez, V. E., Zelechowska, A., & Jensenius, A. R. (2018). Correspondences between music and involuntary human micromotion during standstill. *Frontiers in Psychology, 9*, 1382.

Abstract

The relationships between human body motion and music have been the focus of several studies characterizing the correspondence between voluntary motion

and various sound features. The study of involuntary movement to music, however, is still scarce. Insight into crucial aspects of music cognition, as well as characterization of the vestibular and sensorimotor systems could be largely improved through a description of the underlying links between music and involuntary movement. This study presents an analysis aimed at quantifying involuntary body motion of a small magnitude (micromotion) during standstill, as well as assessing the correspondences between such micromotion and different sound features of the musical stimuli: pulse clarity, amplitude, and spectral centroid. A total of 71 participants were asked to stand as still as possible for 6 min while being presented with alternating silence and music stimuli: Electronic Dance Music (EDM), Classical Indian music, and Norwegian fiddle music (Telespringar). The motion of each participant's head was captured with a marker-based, infrared optical system. Differences in instantaneous position data were computed for each participant and the resulting time series were analyzed through cross-correlation to evaluate the delay between motion and musical features. The mean quantity of motion (QoM) was found to be highest across participants during the EDM condition. This musical genre is based on a clear pulse and rhythmic pattern, and it was also shown that pulse clarity was the metric that had the most significant effect in induced vertical motion across conditions. Correspondences were also found between motion and both brightness and loudness, providing some evidence of anticipation and reaction to the music. Overall, the proposed analysis techniques provide quantitative data and metrics on the correspondences between micromotion and music, with the EDM stimulus producing the clearest music-induced motion patterns. The analysis and results from this study are compatible with embodied music cognition and sensorimotor synchronization theories, and provide further evidence of the movement inducing effects of groove-related music features and human response to sound stimuli. Further work with larger data sets, and a wider range of stimuli, is necessary to produce conclusive findings on the subject.

Discussion

This paper followed the main ideas of Paper I, as it was also based on the Championship of Standstill paradigm (2017 edition). This was the first research experiment conducted as part of the then newly started MICRO project, which I took part in organising. Here, the design of the Championship paradigm and the analysis of data were developed further.

The main change in the paradigm design was in the method of presenting sound stimuli. They were presented in a randomised order and alternated with silence segments. This limited the potential effect of tiredness, which was a limitation in Paper I, as well as any potential effect of the order of stimuli. In this paper, differences in movement to individual stimuli were studied in detail. We chose three substantially different music genres. EDM is characterised by a steady pulse based on the 'four on the floor' beat pattern, a high amount of low frequencies, and, often, a break routine. Telespringar (Norwegian folk music played on fiddle) is also dance music, but its beat pattern is asymmetrical and rather elusive to a listener who is not familiar with this type of music. Finally, the Indian vocal music track used is robust in melodic features, but it is not made for dance and lacks a clear rhythmic structure.

To quantify some of the differences between these audio tracks, several music features, such as loudness, brightness, pulse clarity, and tempo, were extracted with the Music Information Retrieval (MIR) toolbox (Lartillot & Toiviainen, 2007; Lartillot et al., 2008). The focus was on features that have been previously associated with motor entrainment to music and the feeling of groove (Stupacher et al., 2016; Ross et al., 2016b; Burger et al., 2017). These music features were cross-correlated with the motion capture data to see how they corresponded with each other. This was done by measuring the similarities between the music features and movement time series.

The results of this study replicated those from Paper I and showed that people move more to music than in silence. Looking at the differences between genres, we found that this movement-inducing effect was driven by EDM. The movement recorded during the presentation of Indian music and telespringar did not differ significantly from movement recorded in the silence segments. The cross-correlation analyses showed that there were significant differences between stimuli in terms of the similarity between music and movement time series, but only in pulse clarity.

An in-depth study of the stimuli gave additional insights into that features of music—pulse clarity in particular—that encourage (induce) movement. However, the large differences between the genres used could also be seen as a limitation, because it was not possible to study the impact of particular features in detail. A study in which music stimuli were more coherent and from one musical genre, but still varied in their saturation with particular music features, was needed. This thought motivated the design of the sound stimuli for the following Championship in 2018 (Paper A), as well as the Headphones/Speakers experiment (Paper III and Paper IV).

5.2.3 Paper III

Reference: Zelechowska, A., Gonzalez-Sanchez, V. E., Laeng, B. & Jensenius, A. R. (2020). Headphones or speakers? An exploratory study of their effects on spontaneous body movement to rhythmic music. *Frontiers in Psychology, 11*, 698.

Abstract

Previous studies have shown that music may lead to spontaneous body movement, even when people try to stand still. But are spontaneous movement responses to music similar if the stimuli are presented using headphones or speakers? This article presents results from an exploratory study in which 35 participants listened to rhythmic stimuli while standing in a neutral position. The six different stimuli were 45 seconds each and ranged from a simple pulse to excerpts from electronic dance music (EDM). Each participant listened to all the stimuli using both headphones and speakers. An optical motion capture system was used to calculate their quantity of motion, and a set of questionnaires collected data about music preferences, listening habits, and the experimental sessions. The results show that the participants on average moved more when listening through headphones. The headphones condition was also reported as being more tiresome by the participants. Correlations between participants' demographics, listening habits, and self-reported body motion were observed in both listening conditions. We conclude that the playback method impacts the level of body motion observed when people are listening to music. This should be taken into account when designing embodied music cognition studies.

Discussion

This paper starts with a long background section on the differences between headphones and speakers. In the process of designing the experiment, it occurred to me that these playback devices are different in many ways; each device provides different physical, psychoacoustical, and social experiences. This section of the article explain these differences in detail.

The following section describes how headphones and speakers are typically used in music listening studies, with particular attention given to experiments on embodied music cognition. Apart from the playback method, another area of focus is loudness settings and their importance in such experiments. A large table summarises the playback methods used in various relevant studies on body movement to music.

Next, the paper provides an overview of existing studies that compare headphones and speakers as playback methods. To my knowledge, this is the first attempt to summarise such studies. The main message from this section is that it has already been shown that using these two playback systems for listening paradigms can lead to different results, and that none of the existing comparative studies focus on bodily responses to music or body movement to music.

The last part of the introduction briefly explains our approach to body movement as a spontaneous response to music. It summarises our previous findings from the Championships of Standstill and shows that there are already some studies that approach body movement as a spontaneous response to music. The introduction closes with a brief explanation of our interest in particular music stimuli, individual differences, and movement measures.

The following sections of the paper present the design and main results from the Headphones/Speakers experiment. Each participant experienced two listening sessions—with headphones and with speakers—and their body movement was recorded with an infrared optical motion capture system. As explained in Section 4.2.2 and in the paper, several other sensors were also used: a balance board, EMG, and a breathing sensor. There are several reasons why Paper III does not include analyses of these data. First, the paper, with its robust introduction, was already very long. Second, adding these movement data would have complicated the design of the study, which already had several movement measures from motion capture and a number of other variables. Third, these methods were added as a way of experimenting with movement-sensing technologies. The resulting data required completely different types of analyses that are substantially different to the analysis of data from motion capture and are less documented in the relevant literature.

The sound stimuli in this experiment were mainly from the EDM genre. I decided to focus on this genre based on the results from the previous Championships of Standstill, because it was particularly effective for inducing movement. Moreover, there are several other relevant studies on movement that focus on this genre (Moelants, 2003; Van Dyck et al., 2013; Burger et al., 2017). The idea here was also to explore the impact of rhythmic/musical complexity. The selected music tracks varied in this aspect, and two additional tracks were made to complete the range of complexity from very low (synthetic beat track and drum track) to very high (two EDM tracks). To simplify the design, in this paper, we divided the stimuli according to complexity (high and low).

The main finding of this paper is that more body movement was observed during the headphones listening sessions. This difference was particularly large for head movement, but also significant for the average movement from all markers. There are several potential reasons for this difference which are explained in the discussion. Body movement in response to high and low complexity stimuli did not significantly differ. The headphones listening session was reported as being more tiresome. Other analyses showed that people experience the two playback methods differently in everyday life. The most important takeaway from this study is that using headphones and speakers can, indeed, lead to different results in embodied music cognition studies.

5.2.4 Paper IV

Reference: Zelechowska, A., Gonzalez-Sanchez, V. E., Laeng, B., Vuoskoski, J. K. & Jensenius, A. R. (2020). Who moves to music? Empathic Concern predicts spontaneous movement responses to rhythm and music. *Music & Science, 3.*

Abstract

Moving to music is a universal human phenomenon, and previous studies have shown that people move to music even when they try to stand still. But are there individual differences when it comes to how much people spontaneously respond to music with body movement? This article reports on a motion capture study in which 34 participants were asked to stand in a neutral position while listening to short excerpts of rhythmic stimuli and electronic dance music (EDM). We explore whether personality and empathy measures, as well as different aspects of music-related behaviour and preferences, can predict the amount of spontaneous movement of the participants. Individual differences were measured using a set of questionnaires: Big Five Inventory (BFI), Interpersonal Reactivity Index (IRI), and Barcelona Music Reward Questionnaire (BMRQ). Liking ratings for the stimuli were also collected. The regression analyses show that Empathic

Concern is a significant predictor of the observed spontaneous movement. We also found a relationship between empathy and the participants' self-reported tendency to move to music.

Discussion

This paper further explores the data gathered during the Headphones/Speakers experiment. In this experiment, many different questionnaires were used; they measured not only preferences for, and habits associated with, using headphones and speakers, but also concepts such as personality, empathy, styles of engaging with music, and other individual differences. The initial idea was to include the analysis of these variables in Paper III. However, as Paper III grew longer and more detailed, we realised that it would be too much, and that it should be discussed in a separate article.

After some consideration, for Paper IV, movement data from the headphones and speakers listening sessions were averaged for each participant. Moreover, instead of using three different movement measures as in Paper III, the averaged movement of markers on the whole body was used as the dependent variable. Two main factors motivated these decisions. First, there were already many variables in the analysis. Second, we decided that the topic of individual differences in spontaneous movement responses to music is interesting and novel on its own, without getting into the details of the differences between headphones and speakers.

Several previous studies have shown interesting relationships between individual differences and body movement to music (Luck et al., 2009, 2010; Carlson et al., 2016; Bamford & Davidson, 2017). However, these studies mainly, and only partially, answered the following question: Does the manner in which different people move to music depend on their traits? Here, we asked a different question: What kind of person is likely to spontaneously move to music? To test this, we built a regression model in which a selection of variables—personality traits, different kinds of empathy components, styles of drawing reward from music, and liking of the stimuli—were tested as predictors for the amount of movement observed with motion capture. We ran such regressions separately for the EDM stimuli and for the control beat track. Moreover, in order to compare how these variables predict the *self-reported* tendency to move to music, we built another regression model in which personality and empathy traits were tested as predictors for the Sensory-Motor subscale from the Barcelona Music Reward Questionnaire.

The results showed that the amount of body movement, both to EDM and the beat track, can be significantly predicted by Empathic Concern (i.e., a tendency to sympathise with others). Interestingly, Empathic Concern also predicted participants' self-reported tendency to move to music. This finding is particularly interesting in light of the recent findings from Bamford & Davidson (2017), where highly empathic participants were shown to be better at synchronising their movement to music. It opens up discussions on whether empathic people are more receptive to the beat in music, and furthermore, whether listening to music is a social activity, even when the listener is completely alone.

5.2.5 Paper V

Reference: Zelechowska, A., Gonzalez-Sanchez, V. E. & Jensenius, A. R. (2020). Standstill to the 'beat': differences in involuntary movement responses to simple and complex rhythms. In *Proceedings of the 15th International Conference on Audio Mostly* (pp. 107-113).

Abstract

Previous studies have shown that movement-inducing properties of music largely depend on the rhythmic complexity of the stimuli. However, little is known about how simple isochronous beat patterns differ from more complex rhythmic structures in their effect on body movement. In this paper we study spontaneous movement of 98 participants instructed to stand as still as possible for 7 minutes while listening to silence and randomised sound excerpts: isochronous drumbeats and complex drum patterns, each at three different tempi (90, 120, 140 BPM). The participants' head movement was recorded with an optical motion capture system. We found that on average participants moved more during the sound stimuli than in silence, which confirms the results from our previous studies. Moreover, the stimulus with complex drum patterns elicited more movement when compared to the isochronous drum beats. Across different tempi, the participants moved most at 120 BPM for the average of both types of stimuli. For the isochronous drumbeats, however, their movement was highest at 140 BPM. These results can contribute to our understanding of the interplay between rhythmic complexity, tempo and music-induced movement.

Discussion

This paper is based on the data from the 2019 edition of the Championship of Standstill. The main research design was the same as in previous editions: comparing involuntary movement of people standing still in silence and when listening to sound stimuli. For this edition, I suggested to produce all stimuli using an open database of samples recorded from different types of drums. Apart from the isolated sounds of single drums, this database comprised sequences of rhythms played manually on each type of drum. This made it possible to create highly naturalistic stimuli. In the paper, we refer to them as complex drum patterns, but this does not fully reflect the highly musical quality of this stimuli.

The main inspiration behind the design of the stimuli was the music played by the Japanese taiko drummers. Such music is associated with large, expressive movement of the body, and thus, I expected it to have movement-inducing properties. At the same time, the idea of using only drums fit well with one of the general goals of the Championship studies, which is to control for the impact of individual music features on body movement. Using drum samples made it possible to have a partial control over the tempo and rhythmic complexity, while at the same time avoid the (potential) impact of melody and harmony. As it turned out, however, some differences in the original drum samples made it difficult to produce stimuli with systematic use of rhythmic patterns across different tracks.

Apart from the three produced tracks of 'drum music', I produced three tracks of isochronous drumbeats. Each track comprised only one sound of a selected drum, looped over 30 seconds. Thus, it resembled a 'metronome' track. However, our goal was to use stimuli that would be coherent with the other tracks in terms of ecological and musical qualities, and would feel less boring to listen to than a typical metronome track. We also wanted all tracks to have a similar amount of low-frequency content. When a standard, high-pitched metronome sound is used in comparison to music, it is often quite different in spectral content when compared to the rest of the stimuli. Our approach therefore follows the similar logic as that by Zentner & Eerola (2010), who also used isochronouos drumbeat tracks instead of a metronome in their study on movement responses in infants.

The first research question of this study concerned the difference between involuntary movement in the silence and sound conditions. As hypothesised, we found that people moved more when they listened to sound stimuli than in silence. This result was significant not only for the average of all stimuli, but also individually for each of the two types of stimuli: isochronous rhythms and complex drum rhythms. This gave further evidence for the findings of our previous studies based on the paradigm of the Championship of Standstill (Papers I, II and Paper A), that music with clear and prominent rhythmic structures induces movement in participants trying to stand still. Furthermore, Zentner & Eerola (2010) also found that both isochronous drumbeats and rhythmic music induce movement in infants. Our second research question pertained to the differences between isochronous sounds and complex rhythms in terms of their potential movement-inducing properties. We found that complex rhythms induce more movement than isochronous drumbeats. These findings correspond well to studies on groove and syncopation, showing that people feel like moving mostly to rhythms of optimal complexity—neither too simple, nor too complex (Witek et al., 2014; Sioros et al., 2014). Finally, we examined the role of tempo in inducing movement responses to music. We found that people moved most to stimuli at 120 BPM, suggesting that this tempo is, indeed, particularly resonant with the human sensorimotor system, perhaps because it is the natural tempo for walking (MacDougall & Moore, 2005; Styns et al., 2007; Larsson et al., 2019). In the paper, we propose several potential explanations for this finding, and suggest exploring interactions between rhythmic complexity and tempo in the future studies on movement responses to music.

5.3 Other Papers (Not Included in the Thesis)

In addition to the papers above, which are included as part of my dissertation, I have also contributed to several other papers as part of the MICRO project. These are described below, since they shed light on my contributions and the larger picture of which my dissertation is one part.

5.3.1 Paper A

Reference: González Sánchez, V., Żelechowska, A., & Jensenius, A. R. (2019). Analysis of the Movement-Inducing Effects of Music through the Fractality of Head Sway during Standstill. *Journal of Motor Behavior*, 1-16.

Abstract

The links between music and human movement have been shown to provide insight into crucial aspects of human's perception, cognition, and sensorimotor systems. In this study, we examined the influence of music on movement during standstill, aiming at further characterizing the correspondences between movement, music, and perception, by analyzing head sway fractality. Eighty seven participants were asked to stand as still as possible for 500 seconds while being presented with alternating silence and audio stimuli. The audio stimuli were all rhythmic in nature, ranging from a metronome track to complex electronic dance music. The head position of each participant was captured with an optical motion capture system. Long-range correlations of head movement were estimated by detrended fluctuation analysis (DFA). Results agree with previous work on the movement-inducing effect of music, showing significantly greater head sway and lower head sway fractality during the music stimuli. In addition, patterns across stimuli suggest a two-way adaptation process to the effects of music, with musical stimuli influencing head sway while at the same time fractality modulated movement responses. Results indicate that fluctuations in head movement in both conditions exhibit long-range correlations, suggesting that the effects of music on head movement depended not only on the value of the most recent measured intervals, but also on the values of those intervals at distant times.

Discussion

This paper is based on data from the 2018 edition of the Championship of Standstill. In this edition, the same music stimuli were used as in the Headphones/Speakers experiment, and were presented in the same way (alternating segments of silence and music, randomised order of tracks, etc.; the details are described in Section 4.2.1). In this paper, the approach to the analysis of standstill data is different from that in Paper I and Paper II. Here, the fluctuations in head movement data are analysed using a detrended fluctuation analysis. The idea was to investigate whether such fluctuations have fractal properties, and how they are affected by music.

In fractals, fluctuations occur over a range of timescales; similar patterns repeat at multiple scales of measurement (Van Orden et al., 2011). Previous work has shown that human movement has fractal properties that can be affected by various sensory stimuli. While there have been studies on sound affecting human movement fractality, no previous studies have investigated the impact of music.

The results revealed the existence of fractal-like organisation of head movement during standstill. The fractal properties of such fluctuations were significantly larger in vertical movement when compared to those in the anterio-posterior and medio-lateral directions. Additionally, there were significant differences in fractal properties between the music and silence conditions, showing the effect of music on the dynamics of human head motion.

This is one of the first studies investigating the dynamics of spontaneous human movement in the context of music perception. Its results confirm the findings from Paper I and Paper II about the movement-inducing properties of EDM music. While I took part in the data collection and processing of data, I was not so involved in the data analysis. Therefore, I decided not to include the paper in the dissertation.

5.3.2 Paper B

Reference: Gonzalez Sanchez, V., Żelechowska, A., & Jensenius, A. R. (2018). Muscle activity response of the audience during an experimental music performance. In *Proceedings of the Audio Mostly 2018 on Sound in Immersion and Emotion* (pp. 1-4).

Abstract

This exploratory study investigates muscular activity characteristics of a group of audience members during an experimental music performance. The study was designed to be as ecologically valid as possible, collecting data in a concert venue and making use of low-invasive measurement techniques. Muscle activity (EMG) from the forearms of 8 participants revealed that sitting in a group could be an indication of a level of group engagement, while comparatively greater muscular activity from a participant sitting at close distance to the stage suggests performance-induced bodily responses. The self-reported measures rendered little evidence supporting the links between muscular activity and live music exposure, although a larger sample size and a wider range of music styles need to be included in future studies to provide conclusive results.

Discussion

This paper presents data from the first edition of MusicLab (see Section 4.1 for information about the MusicLab paradigm). This edition of MusicLab centred around ‘Biophysical Music’. Data were collected from 10 volunteers who participated in a concert combined with a research experiment and a panel discussion about the phenomenon of biophysical music. The data collection included putting EMG sensors on the dominant forearms of the participants and distributing short questionnaires after the concert. Participants were asked to behave naturally during the event. EMG data were recorded during a performance by Marco Donnarumma of two music pieces played on a biophysical instrument that he had designed. The instrument was based on the sonification of the performer's muscles. It was placed on both arms of the performer and played when he moved his arms in space. We were interested in exploring whether the music would evoke similar muscular activity in the arms of audience members. The data recorded during music listening was contrasted against baseline data collected during the panel discussion. In this way, it was possible to narrow the focus to include only those aspects of movement that were likely to be related to the experience of music.

The study showed increased muscular activity among participants sitting in groups and those sitting close to the stage. While these results are interesting, they should be treated with caution. First, the number of participants in this study was small (the final sample only included eight participants). Second, this was our first attempt at doing data collection in a public venue, which is methodologically challenging in many ways. Participants were free to move around in space; for example, to go to the bar to get a beverage. This influenced the data collected from the sensor and resulted in a lot of noise in the data. For these reasons, this paper was not included in the thesis. As I see it, the main value of this paper was not in the collected data, but in embracing a new method of studying spontaneous responses to music outside of the motion capture laboratory.

5.3.3 Paper C

Reference: Jensenius, A. R., Gonzalez Sanchez, V. E., Zelechowska, A., & Bjerkestrand, K. A. V. (2017). Exploring the Myo controller for sonic microinteraction. In *Proceedings of the International Conference on New Interfaces for Musical Expression* (pp. 442-445). Aalborg University Copenhagen.

Abstract

This paper explores sonic microinteraction using muscle sensing through the Myo armband. The first part presents results from a small series of experiments aimed at finding the baseline micromotion and muscle activation data of people being at rest or performing short/small actions. The second part presents the prototype instrument MicroMyo, built around the concept of making sound with little motion. The instrument plays with the convention that inputting more energy into an instrument results in more sound. MicroMyo, on the other hand, is built so that the less you move, the more it sounds. Our user study shows that while such an 'inverse instrument' may seem puzzling at first, it also opens a space for interesting musical interactions.

Discussion

This paper explores the idea of using micromotion to control musical instruments (see also Paper D). It documents the development of the first ‘inverse’ music instrument in the MICRO project. The instrument prototype presented here is named MicroMyo, and uses a Myo armband to transform muscle tension into sound. The Myo armband is a commercially available product which enables using gestures to control applications on phones and computers. It contains eight EMG sensors and an inertial measurement unit with a 3D accelerometer and a 3D gyroscope.

First, the paper presents a set of experiments aimed at measuring muscle activity in various static and dynamic positions (sitting still, standing still, sitting and clenching fists, spreading fingers with arms rested on the table, etc). The purpose was to distinguish the EMG data from a range of subtle gestures to inform the design of the instrument.

The second section of the paper describes the development of the instrument. MicroMyo is controlled in the graphical programming environment Max by Cycling ’74, using both existing and self-made patches to transcribe signals from the Myo armband into sound. It is programmed in such a way that motion silences the instrument. A person needs to remain still for a period of time in order to obtain any sound, and once stillness is established, some features of the sound can be controlled by minute, slow and controlled gestures. The pitch is controlled by arm rotation, and moving the arm up and down produces a subtle reverb effect. In this way, the instrument explores the use of both stillness and micromotion to play music.

5.3.4 Paper D

Reference: Gonzalez Sanchez, V. E., Martin, C. P., Zelechowska, A., Bjerkestrand, K. A. V., Johnson, V., & Jensenius, A. R. (2018). Bela-based augmented acoustic guitars for sonic microinteraction. In *Proceedings of the International Conference on New Interfaces for Musical Expression* (pp. 324-327). Virginia Tech.

Abstract

This article describes the design and construction of a collection of digitally-controlled augmented acoustic guitars, and the use of these guitars in the installation *Sverm-Resonans*. The installation was built around the idea of exploring ‘inverse’ sonic microinteraction, that is, controlling sounds through the micromotion observed when trying not to move. The setup consisted of six acoustic guitars, each equipped with a Bela embedded computer, an infrared distance sensor, an actuator attached to the guitar body, and a battery pack. The result was a set of completely autonomous instruments that were easy to hang in a gallery space. The installation encouraged explorations on the boundary between the tactile and the kinesthetic, the body and the mind, and between motion and sound. The use of guitars, albeit with a nontraditional ‘performance’

technique, made the experience both familiar and unfamiliar at the same time. Many users reported heightened sensations of stillness, sound, and vibration, and that the ‘inverse’ control of the instruments was both challenging and pleasant.

Discussion

This paper, like Paper C, fits into another part of the MICRO project, where art meets science. Apart from researching music cognition, the MICRO project aims to explore micromotion for artistic purposes and to develop technologies that facilitate using micromotion to control musical instruments. Self-playing guitars are great examples of combining these two goals. This paper describes the first versions of the instruments, exhibited as an interactive sound installation during the Ultima Oslo Contemporary Music Festival in 2017. The interaction with the instruments is unusual, based on the idea of an ‘inverse’ instrument. Contrary to ‘traditional’ instruments, the guitars play when the person remains still. The longer a person stands motionless in front of the guitar, the more sound it emits.

This paper presents the artistic concept of the guitar installation and explains how it was achieved from a technical point of view. Each guitar is equipped with a Bela micro-computer. An actuator, which is glued to the back of the guitar’s body, amplifies sounds transmitted to it from the Bela. Moreover, as this installation is interactive, the guitars are equipped with optical sensors that detect movement of the person standing in front of them. The guitars are suspended from the ceiling by thin strings. Visitors are invited to come close and hold one of the instruments to stop it from spinning, and to begin the interaction. After describing this physical setup, the paper explains the details of programming the Bela micro-computer in order to process movement from the sensor and to obtain the desired sound.

There have been several other installations of the self-playing guitars, to which I have contributed. We have also performed with the guitars on several occasions (see Figure 5.1 for the installation at Ultima Oslo Contemporary Music Festival, and Section 4.1 for more examples).

Figure 5.1: A photograph taken during the installation at Ultima Oslo Contemporary Music Festival. Interaction with the guitar involves remaining still in front of the instrument. Once stillness is established, several layers of sounds slowly develop. Four of the six creators of the installation are visible in the photograph (from left to right): me, Charles Martin, Victor Gonzalez Sanchez, and Kari Anne Bjerkestrand.

Chapter 6

Discussion

The main objective of this dissertation was to observe subtle body movements appearing spontaneously during music listening to expand our understanding of the human tendency to move to music. The empirical papers presented in the second part of this dissertation featured interesting data on several aspects of movement responses to music (see Chapter 5 for discussions on each paper). Below, insights from these papers will be summarised according to the main research questions, followed by a general discussion. In the last part of this chapter, I will reflect on the limitations of the presented approach to studying movement responses to music and suggest some directions for future work.

6.1 Summary

In Chapter 1, I proposed several research questions (Section 1.2). Now, I would like to reflect on the insights that this dissertation provides into each question.

6.1.1 Does music make us move?

The short answer to this question is that music does indeed make us move. More precisely, the evidence gathered for this dissertation confirms that listening to music can *induce* movement, at least by increasing naturally occurring spontaneous motion in the human body.

Papers I, II and V present results from motion capture experiments in which the task was to stand as still as possible. In each of these experiments we observed that participants moved more when listening to music or other rhythmic sound stimuli compared to silence. These findings show that movement to music can be involuntary and thus support the assumption of the *irresistible* quality of movement, which can often be seen in studies on groove. They also confirm the assumption of the *movement-inducing* properties of music. Such a claim is often made in studies on free, non-choreographed movement, in which participants are usually *asked* to move to music. Thus, the induction of movement by music is *assumed* in these studies, rather than being based on empirical data or evidence in the literature. Indeed, the literature review showed that such evidence is available, as a few studies have examined the spontaneous emergence of music-induced movement in body parts, happening without instruction. However, in all but one of these identified studies, movement responses to music were not the main research focus. Furthermore, a study that focused specifically on movement responses to music (and on the whole body rather than specific body parts) was conducted with infants (Zentner & Eerola, 2010), but no analogous studies have examined adults. Thus, the experiments conducted for this dissertation are important contributions to the understanding of the nature of movement responses to music in a general population.

Papers III and IV are based on an experimental paradigm in which there was no instruction to move, but also no instruction to remain as still as possible. The goal was to examine whether participants would spontaneously move to music, even though the experimental instructions did not specifically encourage or discourage such a response. As it turned out, it was not possible to compare movement to music to movement in silence in these studies, as many participants treated the silences as breaks (which was confirmed by the participants themselves and was visible in their body movement data). However, data from the experiments presented in these two papers provide insights on the other three research questions (RQ1, RQ2 and RQ3).

6.1.2 RQ1: What features of musical sound are needed to induce movement?

The exploration of the aspects of musical sound that contribute to movement responses was done in several ways: by comparing music and silence (see Section 6.1.1), music genres, music features, and rhythm and music.

Previous studies on the impact of music on body movement typically used popular music associated with dancing, or that was considered groovy (i.e, inducing a pleasurable sensation of wanting to move to the beat, or an urge for such movement). The experiments in this dissertation, however, used a variety of genres, including some that are not usually associated with dancing or that have complex underlying rhythmic structures not characteristic of popular music. A comparison across genres in Paper II showed that EDM induced more movement in participants who were standing still than did Norwegian folk music (telespringar) or vocal Indian music. Results from Paper I also indicate that EDM is a particularly movement-inducing type of music, but due to limitations in the study design, it was not possible to perform a systematic comparison between genres in this study. EDM is characterised by a clear rhythmic layer with a strong underlying pulse, rich in low-frequency content. Previous studies have shown that these musical qualities have a significant impact on body movement—they increase its intensity and improve synchronisation with the beat. Moreover, EDM is a music genre that is associated with dancing, and it is often created with the goal of encouraging people to move without needing to learn any specific choreography. After confirming its movement-inducing properties, we decided to focus on this genre in the experiment presented in Papers III and IV (as well as Paper A, which is not included in this dissertation).

Looking at particular music features, we observed that pulse clarity significantly increased people's involuntary movement to music (Paper II). Features such as brightness and loudness did not explain how much participants moved. One feature that was given particular attention in this dissertation was rhythmic complexity. The main contribution of the present work is in comparing the impact of real music with that of simple isochronous beats, and with stimuli that are in between these two extremes in their musical and rhythmic complexity.

In Paper III, a range of stimuli with different rhythmic complexity was used. For the analyses, these stimuli were grouped in two categories of rhythmic complexity: low and high. We did not observe a significant difference in how much participants spontaneously moved to both types of stimuli. In Paper V, the stimuli were also put into two categories of rhythmic complexity. In this paper, however, the low rhythmic complexity stimuli comprised only isochronous beat tracks, which constitute the lowest possible complexity of rhythm (one sound repeating at constant time intervals). Compared to complex drum patterns, resembling real music played on taiko drums, the low-complexity stimuli induced less involuntary movement in participants. However, participants moved more to both types of stimuli than in silence. This suggests that even simple beats can have movement-inducing properties, but these are less prominent than those of more complex rhythmic stimuli resembling real music.

Paper V shows how tempo can impact involuntary body movement. The 120 BPM stimuli induced more movement than stimuli at 90 BPM or 140 BPM. These results corroborate previous hypotheses that the 120 BPM tempo is particularly resonant with the human sensorimotor system. For isochronous beats, however, there was more movement to the 140 BPM stimulus. These findings suggest that there may be interactions between rhythmic complexity and tempo that have an impact on spontaneous movement.

6.1.3 RQ2: What traits of listeners make them likely to spontaneously move to music?

Across the five papers included in this dissertation, four included some measures of individual differences (Papers I–IV), and one study focused specifically on that topic (Paper IV). The results of Paper IV suggest that empathy is related to an increased amount of spontaneous movement during music listening. One of the emotional aspects of empathy—Empathic Concern—emerged as a significant predictor of movement. Furthermore, empathy also predicted scores in a self-report measure in which participants reported how much music inspires them to move in their daily life. These findings are in agreement with previous research which showed that empathy plays a significant role in synchronising with the beat in music, and also influences emotional responses to music. Indeed, empathy might facilitate the process of rhythmic entrainment, as both are based on attuning to the actions of other agents. If moving together to music increases social bonding, as research suggests, perhaps empathic participants have a predisposition to move to music. Furthermore, some researchers speculate that movement to music is mediated by the mirror neuron system, which links perception of action through auditory or visual cues with the motor execution of the same action. This topic is worth investigating further in the future.

Previous studies have indicated that Openness to Experience makes people more prone to experiencing chills, entailing various physiological sensations, while listening to music. It has also been shown that, for example, people scoring high in Extraversion move more vigorously in a free dance task. However, in this dissertation, none of the Big Five personality traits connected with movement responses to music. Furthermore, contrary to hypotheses based on previous research, preference for the music stimuli did not have a significant effect on how much participants moved. Styles of engaging with music, years of music training and gender also did not emerge as important factors.

In some data sets, age (Papers I–III), height (Paper II and III), the amount of time spent on physical exercise (Paper I) and liking to dance (Paper III) correlated positively with the amount of movement. These results indicate that body morphology and fitness might be related to spontaneous movement to music. However, particularly in the case of Papers I and II, these factors might well be connected to the ability to stand still rather than to the influence of music, as some correlations were observed for both the music and silence segments. These factors should be explored further in future studies on movement responses to music.

6.1.4 RQ3: What context of music experience encourages body movement?

The main type of music experience context examined in this dissertation was the use of particular playback technologies. Paper III shows that the participants moved more when listening to music through headphones than speakers. Using data only from this study, it is not possible to determine the reason for such a result. Perhaps it can be explained by the impact of headphones on the human balance system, aesthetic or emotional responses to music, or sociopsychological factors. Most importantly, it shows that using different playback technologies can alter the experience of music, including spontaneous movement responses. While a comparison of headphones and speakers seems fairly niche, it opens up a discussion on a number of different listening contexts, such as the social context of music listening and the physical surroundings of the listener.

The social context of music experience was not explored systematically in this dissertation, but it has been discussed from various perspectives. In Paper III, we reflect on whether the movement intensified in the headphones condition because participants were able to forget about the presence of experimenters when wearing headphones and be less conscious of their movement, and/or more focused on the music experience. Furthermore, the experiments in Papers I, II and V were conducted in groups. In Papers I and II, we controlled for the effect of the group on observed movement and did not find significant differences between groups. In Paper II we also controlled for participants' positions within the laboratory space. This was to ensure that there was no bias in the data between standing spots, either due to the way the motion capture system was calibrated or because of the standing position in relation to other participants. For example, participants in the second and third rows could see the bodies of the participants standing in front of them, while participants in the first row could only see the wall. This factor also turned out not significant. However, in one of the experiments, we observed that a participant who started laughing made the other participants laugh, too. We subsequently decided to exclude this group from the analyses, but this occurrence made us wonder as to whether there are other interactions between individuals, whether clearly observable or not, that influence their movement. Perhaps seeing a person moving to music, even very subtly, can encourage movement in the perceiver.

It is noteworthy that the papers presented in this dissertation were based on two different approaches to measuring movement responses to music. In some experiments (Papers I, II and V), participants were asked to stand as still as possible. In another experiment (Paper II and III), there was no specific instruction to move or stand still. This also can be viewed as a context of music experience that influences body responses to music. Although we did not perform a systematic comparison of the movement data between the studies, by looking at the average values of the amount of movement, it seems that movement responses to music are more prominent if there is no instruction to suppress movement. This is not surprising, although one could speculate that the inability to express movement could, in turn, increase the urge to move. This is a topic worth investigating further.

Last but not least, in all the studies presented here, the context of being in a motion capture laboratory might have influenced participants' behaviour. This will be discussed in Limitations (Section 6.3).

6.2 General Discussion

The empirical papers presented in this dissertation, together with evidence from previous research, portray movement responses to music as a complex phenomenon. As can be seen in the literature, this topic can be studied with diverse approaches: theoretical reflections on the origins of dance, neuroimaging studies on sensory-motor connections in the brain, systematising the subjective experiences of the movement-inducing properties of music, measuring various aspects of actual body movement to music, and so on. While studies on movement to music span a broad range of disciplines, I have noticed a communication gap between the fields. For example, in the literature I reviewed for the dissertation, I rarely saw references to posturographic studies showing the impact of music on human balance, and studies on body movement often did not consider the psychological concept of groove. Apart from searching for new perspectives and technologies for studying movement responses to music, building bridges between various disciplines is an important goal for future research. Furthermore, I noticed different understandings of key concepts such as *synchronisation*, *entrainment* and *groove*. While it was beyond the scope of this dissertation to systematise the definitions of these concepts, it was illuminating to notice how differently the same term can be used and understood, and how such discrepancies can disrupt communication in research.

The papers included in this dissertation show that there are multiple factors that contribute to movement responses to music. They can, in general, be grouped into three categories: pertaining to the musical sound, the individual attributes of the listener, and the context of the music experience. Studying each of these three categories is crucial for understanding how music can inspire body movement. While it is beneficial to focus on the role of particular aspects (for example, rhythmic complexity or playback system), it is also important to ‘zoom out’ from time to time and look at the fuller picture of factors that contribute to movement responses to music and the interactions between them. These factors and interactions are probably endless, but systematising and navigating between them from a broader perspective might eventually help to build a model of movement responses to music.

Over the course of this project, my perspective on movement responses to music has evolved. Shortly after I joined the research team, I suggested looking at micromotion and other subtle body movements to music as a type of bodily response. I initially struggled to decide on whether it is a physiological rather than a physical response, but eventually settled on viewing movement as in between—or a combination of—both types of bodily responses. As the years, studies, conferences and various discussions have gone by, I have come to realise that it is possible to view movement responses to music from a variety of perspectives (Section 2.1). The complexity of the topic kept growing as we debated whether movement to music is inherently voluntary or involuntary, if it can be unconscious, whether music *triggers*, *inspires* or *urges* us to move, and so on. One word in particular that stuck with me when I was first thinking about movement to music was *irresistible*. The Cambridge Dictionary defines irresistible as ‘impossible to refuse, oppose, or avoid because it is too pleasant, attractive, or strong’. At the end of the project, I find the term particularly accurate in the context of movement to music, as it tackles some of its important characteristics: it can be difficult to oppose, it is associated with pleasure, and the connection between movement and music seems strong and universal.

6.3 Limitations and Future Work

While designing the experiments discussed in the included papers, I had to make many decisions that influenced the collection and interpretation of data (many of which have been discussed in Chapter 4 and in the individual papers). Some consequences of these decisions were easy to anticipate, but others I did not predict. If I were to design and conduct the experiments again, I would do certain things differently. In the following paragraphs, I point out some of the key problems and gaps in the work presented in this dissertation and suggest possible solutions and directions for future research.

The first few issues are epistemological in nature. In this dissertation, *movement responses to music* are understood as behaviour in the presence of certain stimuli (see Section 2.1). This kind of assumption is common in behavioural science research, but it has its limitations. First, it is impossible to determine what other factors (apart from the stimuli) influence the observed behaviour. In this dissertation, the observed movement might have been the result of not (only) the presence of the music stimuli, but also, for example, the mood of the participant, the cup of coffee they had before participating in the experiment or the sudden memory of something. This problem pertains to most studies on *responses to stimuli*. For example, when measuring an emotional response to a picture, researchers do not know the extent to which the participant's emotional state during exposure to the picture is influenced by factors unrelated to the stimulus. Moreover, it is also likely that the emotions felt *before* viewing the picture influence a person's emotional *response* to the picture. The difference between a picture and music is, however, in the timescales of both the stimuli and the responses (singular vs continuous). The probability of bias is increased when studying responses to music, as with a longer observation period, it is more likely that factors unrelated to the stimuli will contribute to the observed behaviour.

Another problem pertains to establishing a baseline for human movement. People cannot stand completely still, so even if they are asked to do so, some movement can still be observed. For this reason, Papers I, II and V include comparisons between movement in silence (baseline movement) and to music. But what is *movement response to music* in these studies? Is it the movement observed during music listening *minus* baseline movement? Or are the two types of movement qualitatively different? If the latter is true, it would not make sense to perform a subtraction of the baseline. These questions are beyond the scope of this dissertation, but they would be worth considering in future studies.

A similar issue can be seen in the experiment discussed in Papers III and IV. With this data set, it made little sense to compare movement in silence with movement to music because some participants treated the silences between stimuli as breaks, probably assuming that only their behaviour during the music playback was being recorded. Thus, some participants fidgeted a lot during the silence condition; sometimes they stretched, scratched their noses and so on. This was quite unlike what happened in the other experiments, in which participants were motivated to stand as still as possible throughout the whole recording session (including silence periods). Without a clear baseline level of movement, perhaps a more objective description of the data discussed in Papers III and IV would be *movement that happens during music experience* rather than *movement responses to music*. However, in both these papers, we did use the term *movement responses*. Although generally accepted in studies on human behaviour, it is worth considering whether the use of such a term in this type of experimental design is indeed appropriate.

Measures that are missing from this dissertation are those of periodicity and synchronisation of movement to the beat in the stimuli. Across the five papers, we only considered the quantity of motion in the discussion of movement to music. Analysing periodicity could help distinguish between different types of movement (such as body sway, breathing or head bobbing) and possibly separate them from baseline movement of the human body. We made several attempts to study the periodicity of movement in the standstill tasks (one is described in Paper A). However, given the minuscule scale of movement, it was difficult to detect periodicity in the data. As the movement observed in the experiment discussed in Papers III and IV occurred at a slightly larger scale, in the future we plan to search for appropriate periodicity measures to check whether participants' movement aligned with rhythms in the stimuli.

Another limitation of this dissertation is that it covers only a fraction of all the possible variables that could pertain to musical sound, the listener and the context of the music experience. Furthermore, apart from studying individual variables belonging to each topic (music, listener and context) it also seems wise to examine interactions between variables within (e.g., tempo and rhythmic complexity) and across these topics (e.g., tempo and personality traits). Such interactions have only been explored in this dissertation to a limited degree. There are also many more possible approaches to studying movement responses to music, as shown in Chapters 2 and 3. Some of these approaches (e.g., posturography) have not been discussed in depth.

One participant-related factor that could have been given more attention is musical expertise. Several previous studies have shown that there are differences in how musically-trained people move to music compared to those without training. The questionnaire used in this dissertation to measure musical expertise (see BAT in Section 4.3.3) turned out to be a poor fit for our experiments, especially since it was not clear how to calculate the number of years of musical training. Retrospectively, I would have included a more robust measure of music expertise for these experiments—for example, the Ollen Musical Sophistication Index (Ollen, 2006).

In the future, it would be interesting to study movement responses to music outside a laboratory. To study truly *spontaneous* responses, participants should ideally be unaware that their movement was being measured. Using motion capture and motion sensing technologies, inside or outside a laboratory, might prompt participants to assume that some movement is *expected* from them. It would be interesting to explore alternative movement analysis techniques based on video recordings. However, studying minute body movements is difficult even with a high-quality motion capture system. Such systems are designed to record explicit body movements rather than subtle manifestations of small-scale movements. Developing motion capture technologies that use video recordings and are specifically built for studying such movement would aid future studies on spontaneous movement responses to music. In the meantime, it would be interesting to explore the use of different types of sensors designed for measuring physiological processes, such as breathing or muscle activity sensors. This was done in one of the experiments presented in this dissertation, but the resulting data have not yet been analysed.

When working on this dissertation, many paths for further investigations of movement responses to music occurred to me. Apart from experiments that could address some of the shortcomings of the research presented in this dissertation, I have several ideas for future studies.

Expanding on the research questions proposed in this dissertation, it would be interesting to investigate the effects of the spatial properties of sound—for example, by manipulating the location of sounds and/or moving them around. Would such spatialisation techniques have an influence on body movement that is different from that of the two-channel sound distribution used in the current setups? Furthermore, using different types of headphones (e.g., in-ear or noise cancelling) could reveal more about the role of such devices in the embodied experience of music. It would also be interesting to use headphones in a standstill study in which several participants are tested at the same time. As for music features, my next step would be to manipulate the content of low frequencies in the stimuli used in previous studies (e.g., in Paper V) to see how this would influence involuntary movement during standstill. In future studies on individual differences, I would like to further examine the role of empathy in movement to music, and a range of other variables that were not covered in this dissertation, such as sensory processing sensitivity and impulsiveness. It would also be interesting to examine cross-cultural and cross-species differences in movement responses to music. Studies on the latter show promise in advancing the understanding of how the phenomenon of music-related body movement evolved and what biological mechanisms are responsible for it. In sum, many more studies are needed to explain why it can be so irresistible to move to music.

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Papers

Paper I

The musical influence on people's micromotion when standing still in groups

Alexander Refsum Jensenius, Agata Zelechowska, Victor E. Gonzalez-Sanchez

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The musical influence on people's micromotion when standing still in groups

Alexander Refsum Jensenius, Agata Zelechowska, Victor Gonzalez Sanchez
University of Oslo, Department of Musicology, fourMs Lab
`[a.r.jensenius, agata.zelechowska, v.e.g.sanchez]@imv.uio.no`

ABSTRACT

The paper presents results from an experiment in which 91 subjects stood still on the floor for 6 minutes, with the first 3 minutes in silence, followed by 3 minutes with music. The head motion of the subjects was captured using an infra-red optical system. The results show that the average quantity of motion of standstill is 6.5 mm/s, and that the subjects moved more when listening to music (6.6 mm/s) than when standing still in silence (6.3 mm/s). This result confirms the belief that music induces motion, even when people try to stand still.

1. INTRODUCTION

It is commonly assumed that listening to musical sound, and particularly dance music with a clear pulse, ”makes” us move. This assumption is to some extent supported by the literature in embodied music cognition [1, 2], and there are also empirical studies of music-induced motion [3, 4] or motion enhanced by music [5, 6]. Many of these former studies have mainly focused on voluntary and fairly large-scale music-related body motion. As far as we know, there is little empirical evidence of music actually making people move when they try to remain at rest.

Our aim is to investigate the tiniest performable and perceivable human motion, what we refer to as *micromotion*. Such micromotion is primarily involuntary and performed at a scale that is barely observable to the human eye. Still we believe that such micromotion may be at the core of our cognition of music at large, being a natural manifestation of the *internal* motor engagement [7].

In our previous studies we have found that subjects exhibit a remarkably consistent level of micromotion when attempting to stand still in silence, even for extended periods of time (10 minutes) [8]. The measured standstill level of a person is also consistent with repeated measures over time [9]. These studies, however, were carried out on small groups of people (2–5), so we have been interested in testing whether these findings hold true also for larger groups.

In this paper we report on a study of *music-induced micromotion*, focusing on how music influences the motion of people trying to stand still. In order to answer that question, it is necessary to have baseline recordings of how much people move when standing still in silence. More specifically, this paper is aimed at answering the following questions:

- How (much) do people move when trying to stand still?
- How (much) does music influence the micromotion observed during human standstill?

Figure 1. The setup for the “Norwegian Championship of Standstill.” Each subject wore a reflective marker on the head, and one static marker was recorded from a standing pole in the middle of the space as a reference.

To answer these questions, we have started carrying out a series of group experiments under the umbrella name of the “Norwegian Championship of Standstill.” The theoretical background of the study and a preliminary analysis have been presented in [10]. This paper presents a quantitative analysis of the data from the 2012 edition of our experiment series.

2. THE EXPERIMENT

The experiment was carried out in the fourMs motion capture lab at the University of Oslo in March 2012 (Figure 1).

2.1 Participants

A little more than 100 participants were recruited to the study, and they took part in groups consisting of 5-17 participants at a time (see Figure 1 for a picture of the setup). Not every participant completed the task and there were some missing marker data, resulting in a final dataset of

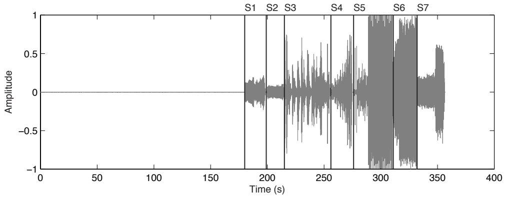

Figure 2. Waveform of the sound used throughout the experiment. Silence for the first 3 minutes, followed by 7 short music excerpts (S1–S7) ranging from non-rhythmic orchestral music to electronic dance music.

91 participants (48 male, 42 female, 1 unspecified).[1] The average age was 27 years (min = 16, max = 67). The participants reported quite diverse numbers for how many hours per week they spent listening to music (*M*=19, *SD*=15) and creating music (*M*=8, *SD*=8), reflecting that around half of the participants were music students.

2.2 Task

The task given to the participants was to attempt to stand as still as possible on the floor for 6 minutes in total, 3 minutes in silence and 3 minutes with music. They were aware that music would start after 3 minutes.

2.3 Sound stimulus

The sound file used as stimulus consisted of 3 minutes of silence, followed by 3 minutes of musical sound. There were 7 short musical excerpts, each with a duration of 20–40 seconds. The first musical excerpts were slow, non-rhythmic orchestral music, while the last ones were acoustical and electronic dance music.[2] As such, the rhythmic complexity and loudness increased throughout the experiment, as can be seen in Figure 2. The sound was played comfortably loud from a pair of Genelec 8020 loudspeakers and a Genelec 7050 subwoofer.

2.4 Motion capture

Each participant wore a reflective marker on his/her head, and its position was recorded using a Qualisys infrared motion capture system (Oqus 300) running at 100 Hz. We have previously shown that the spatial noise level of the system is considerably lower than that of human standstill [11].

Data was recorded and preprocessed in the Qualisys Track Manager, and the analysis was done in Matlab using the MoCap Toolbox [12].

To illustrate how the normalized position data looks like, Figure 3 shows plots of position on the three axes over time, as well as position spatial plots of the three planes.

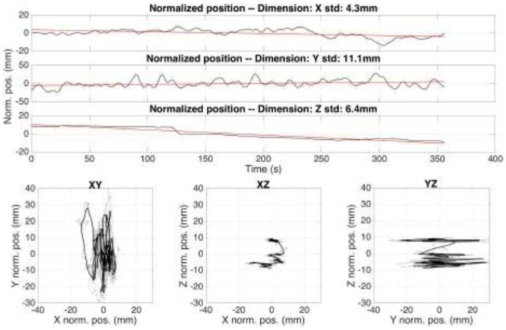

Figure 3. Example plots of the X (sideways), Y (front-back) and Z (updown) axes of the normalized position of a head marker. The light grey line is the raw data; the black line results from a ten-second smoothing; and the red line shows the linear regression (the trend) of the dataset.

3. RESULTS

3.1 Quantity of motion

To answer the question of *how much* people move, we calculated the *quantity of motion* (QoM) of each reflective marker by summing up all the differences of consecutive samples for the magnitude of the position vector, that is, the first derivative of the position:

$$QoM = \frac{1}{T} \sum_{n=2}^{N} \parallel p(n) - p(n-1) \parallel$$

where p is either the two-dimensional (XY axes—the horizontal plane) or three-dimensional (XYZ axes) position vector of a marker, N is the total number of samples and T is the total duration of the recording. The resultant QoM is measured in millimetres per second (mm/s).

In our previous studies [8, 9], we found QoM values in the range of 5–7 mm/s for a small group of people. Our new results confirm this range, with an average QoM of 6.5 mm/s (*SD* = 1.6 mm/s) over the complete recording, as summarised in Table 1. The lowest result was 3.9 mm/s (the winner!) and the highest was 13.7 mm/s. These values, however, included both the no-sound and sound conditions, so Table 1 also shows a breakdown of the values in these two conditions, as well as for the individual sound tracks. These differences will be further discussed in Section 3.5.

3.2 Motion over time

An interesting finding is that, for most participants, the quantity of motion did not change much over time, which can also be seen in the cumulative distance plots in Figure 4. There were a few extreme cases, but most participants had consistent linear motion distribution over time. Coefficient of determination (R-Squared) values were above 0.9 for most participants (mean $R^2 = 0.94$, s.d. $R^2 = 0.0039$ minimum $R^2 = 0.93$).

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[1] This paper is based on the complete dataset, while a subset was used for the qualitative analysis presented in [10].

[2] See `http://www.uio.no/english/research/groups/fourms/downloads/motion-capture/nm2012/` for detailed information about the music excerpts.

Table 1. Mean QoM values (in mm/s) for all sessions, in both no-sound and sound conditions, as well as for each of the individual music sections.

	No sound (3 min)	Sound (3 min)						
Part	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Mean QoM (mm/s)	6.5							
Mean QoM (mm/s)	6.3	6.6						
Mean QoM (mm/s)	6.3	6.2	6.5	6.7	6.5	6.6	6.9	6.7
Standard deviation	1.4	1.8	1.9	1.9	1.7	1.8	3.8	2.3

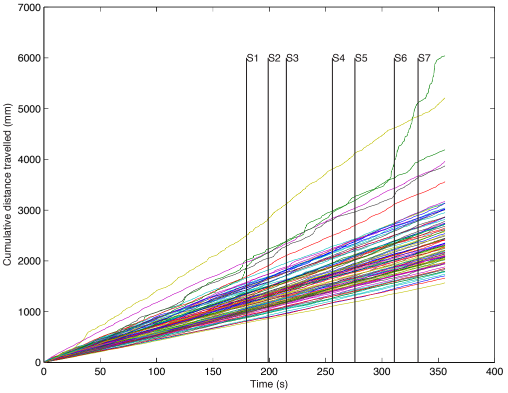

Figure 4. Cumulative distance travelled for all participants.

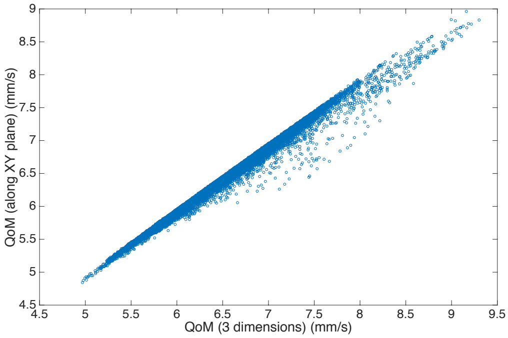

Figure 5. Scatter plot showing the linearity between QoM occurring in the horizontal (XY) plane and three-dimensional (XYZ) for the entire data set.

3.3 Horizontal Motion

To answer the question of *how* people move over time, we computed planar quantity of motion. The horizontal QoM (over the XY plane) was computed for all participants in order to further test the differences between conditions and stimuli. The mean horizontal QoM was found to be 6.4 mm/s for the entire 6-minute recording (*SD* = 1.5 mm/s). This value is only marginally smaller than the 6.5 mm/s found for the 3D QoM, suggesting that most motion, in fact, occurred in the XY plane. The relation between horizontal and 3D motion can also be seen in Figure 5.

3.4 Vertical Motion

To investigate the level of vertical motion, we also calculated QoM along the Z-axis. The mean vertical QoM across participants and conditions was 0.73 mm/s (*SD* = 0.52 mm/s), considerably smaller than the horizontal QoM reported above. This can also be seen in plots of the vertical motion (Figure 7) and in the frontal (YZ) plane (Figure 6), in which the bulk of motion in the Z axis is below 1 mm/s.

When looking at the differences between conditions, the mean vertical QoM during the no-sound segment of the trials was found to be 0.69 mm/s, while for the sound segment it was 0.77 mm/s.

3.5 Influence of sound on motion

For the 3-minute parts without sound we found an average QoM of 6.3 mm/s (*SD* = 1.4 mm/s), as opposed to 6.6 mm/s (*SD* = 2.2 mm/s) for the part with sound. This is not a dramatic difference, but shows that the musical stimuli did influence the level of standstill. A paired sample t-test was conducted to evaluate statistical significance of the observed differences between sound and no-sound conditions across the sample group. The results indicate the differences in means for three-dimensional QoM were significant for a 95% confidence interval ($t = 2.48$, $p = .015$).

Differences in the planar QoM between the sound (6.5 mm/s) and no-sound (6.2 mm/s) segments of the experiment were also statistically significant ($t = 2.5$, $p < .05$), although not considerably larger than those observed from 3D QoM.

These observed differences between sound and no-sound conditions were further explored by conducting a k-means cluster analysis of both 3D and 2D QoM for the entire data set. Using instantaneous QoM as a predictor, two clusters were identified by the implemented algorithm, although, as seen in the silhouette plot in Figure 8, most points in the clusters have silhouette values smaller than 0.3. This indicates that the clusters are not entirely separated, which could be due to the homogeneity of the sample group and the continuous nature of the musical stimuli.

The results are even clearer when looking at the individual stimuli in Table 1, with a QoM of 6.9 mm/s for the electronic dance music sample (#7) and 6.7 mm/s for the salsa excerpt (#8). As such, the results confirm our expectation that “music makes you move.” Even though the result may not be very surprising in itself, it is interesting to see that even in a competition during which the partici-

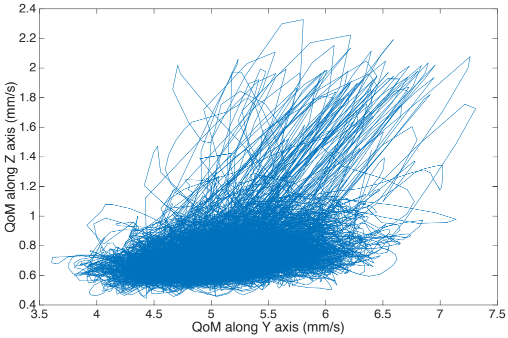

Figure 6. Plot showing QoM in the vertical plane (YZ) for the entire data set. The majority of the motion along this direction was below 1 mm/s.

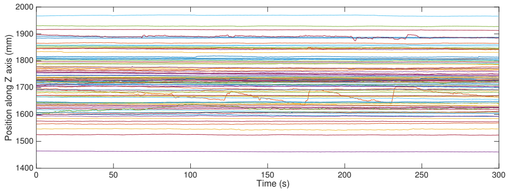

Figure 7. Instantaneous position of the marker along the Z axis (vertical direction).

pants actively try to stand absolutely still, the music has an influence on their motion in what can be termed "micro" level.

3.6 Age, Height and Gender

We found a significant negative correlation between the average QoM results and the participants' age. Generally, younger participants tended to move more (r = -.278, $p < .01$), both in the no-sound (r = -.283, $p < .01$) and sound conditions (r = -.255, $p < .05$). From the reported demographic information, we also found that the younger participants listened to music more frequently (r = -,267, $p <$ .05) and exercised more (r = -.208, $p < .05$). The younger participants also reported feeling less tired during the experiment (r = -.35, $p < .001$), subjectively experienced greater motion (r = -.215, $p < .05$), and also reported moving more when sound was being played (r = -.22, $p < .05$).

Unexpectedly, the QoM results did not correlate with the participants' height, which was estimated by calculating the average of each participant's Z-axis values. Due to a lower centre of mass, we would have expected to see shorter people with lower QoM results. However, the winner was 192 cm tall, while the runner-up was 165 cm.

Also, there were no significant differences in performance between male and female participants (no difference in average QoM, QoM in silence, QoM in music or QoM between both conditions).

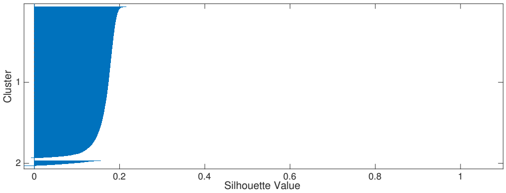

Figure 8. Silhouette plot from k means clustering analysis of QoM along the XY plane for the entire data set.

3.7 Effects of group, posture and physical activity

Aiming to evaluate the effects of standing strategies and postures, the participants were allowed to choose their standing posture during the experiment. In the post-experiment questionnaire they were asked to self-report on whether they were standing with their eyes open or closed, and whether they had their knees locked. The majority of the participants reported that they stood with open eyes (N = 62 versus N = 4 for closed eyes, and N = 8 for those who switched between eyes opened and closed during the experiment). Furthermore, 33 of the participants reported standing with locked knees, 31 switched between open and locked knees and 10 reported standing with their knees open. A 1-way ANOVA was performed to test if any of these factors influenced the average QoM of the participants, but showed no statistically significant results.

Interestingly, the participants who reported greater amount of time spent doing physical exercise tended to move more during the experiment (r = -.299, $p < .01$). This tendency was particularly evident during the no-sound section (r = -.337, $p < .01$), but it was also observed during the sound section (r = -.251, p = < .05).

Additionally, we compared the average QoM results for all conditions (no-sound, sound, average no-sound and sound, and computed difference between sound and no-sound conditions) between groups of participants. Participants were split into 10 groups of varying age ($F(8, 82) = 3.43$, $p <$ .05), experience with performing , composing or producing music ($F(8, 82) = 2.4$, $p < .05$), size (min = 5, max = 17) and the proportion of gender. We found no statistically significant differences between groups across these characteristics.

3.8 Subjective experience of motion

After taking part in the experiment the participants were asked to estimate how much they moved, to what extent the music influenced their movement, and how tiresome the experience felt. Overall, the self-reported tiredness showed some correlation with self-reported motion (r = -.44, $p < .001$) and with the self-reported experience of moving more to music (r = -.289, $p < .01$). The kinematic data confirmed this sensation: the more tired the participants felt, the more they moved to music (r = -.228, $p <$ .05) and the greater was the difference in motion to sound compared to the no-sound conditions (r = -.311, $p < .01$). More importantly, although the subjective experience of motion did not correlate with the measured level of motion, the participants who reported moving more to music did move more during the sound condition when compared to the no-sound condition (r = -.239, $p < .05$ for the difference in QoM between music and silence).

4. CONCLUSIONS

This study was aimed at further exploring the magnitude of micromotion and the influence of music on human standstill, based on the preliminary work presented in [10]. Quantity of motion (QoM) was shown to be a sensitive measure of micromotion for the conditions under analysis. The computation of both three-dimensional and planar QoM showed that micromotion occurred mainly on the horizontal plane. Additionally, statistically significant differences were found between no-sound and sound conditions across the dataset. Two clusters were identified in the data through k-means cluster analysis, although most points in the clusters had silhouette values below 0.4. This could be due to the continuous nature of the sound stimuli and the small (although statistically significant) differences between conditions.

The analysis revealed some relationships between QoM data and the self-reported characteristics of physical activity and demographic information. People who exercised regularly found it more difficult to stand still. Moreover, younger participants tended to move more during both no-sound and sound conditions. These results may suggest that people who tend to be more active struggle to reach and maintain a complete standstill posture, although they might be able to stand normally for longer periods of time and with greater balance. The correlation found between self-reported tiredness and both self-reported and measured motion can not be considered conclusive and further studies will focus on a more in depth assessment of the effects of tiredness in combination with sound stimuli during standstill.

The fact that there were no significant QoM differences between the groups of participants, indicates that testing varying number of participants at once is a viable way to test our hypotheses. Future work will focus on studying larger sample groups and use different stimuli, with a focus on investigating in more depth how different musical features influence the micromotion of people standing still.

Acknowledgments

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Paper II

Correspondences between music and involuntary human micromotion during standstill

Victor E. Gonzalez-Sanchez, Agata Zelechowska, Alexander Refsum Jensenius

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Correspondences Between Music and Involuntary Human Micromotion During Standstill

Victor E. Gonzalez-Sanchez*, Agata Zelechowska and Alexander Refsum Jensenius

RITMO Centre for Interdisciplinary Studies in Rhythm, Time and Motion, Department of Musicology, University of Oslo, Oslo, Norway

The relationships between human body motion and music have been the focus of several studies characterizing the correspondence between voluntary motion and various sound features. The study of involuntary movement to music, however, is still scarce. Insight into crucial aspects of music cognition, as well as characterization of the vestibular and sensorimotor systems could be largely improved through a description of the underlying links between music and involuntary movement. This study presents an analysis aimed at quantifying involuntary body motion of a small magnitude (micromotion) during standstill, as well as assessing the correspondences between such micromotion and different sound features of the musical stimuli: pulse clarity, amplitude, and spectral centroid. A total of 71 participants were asked to stand as still as possible for 6 min while being presented with alternating silence and music stimuli: Electronic Dance Music (EDM), Classical Indian music, and Norwegian fiddle music (Telespringar). The motion of each participant's head was captured with a marker-based, infrared optical system. Differences in instantaneous position data were computed for each participant and the resulting time series were analyzed through cross-correlation to evaluate the delay between motion and musical features. The mean quantity of motion (QoM) was found to be highest across participants during the EDM condition. This musical genre is based on a clear pulse and rhythmic pattern, and it was also shown that pulse clarity was the metric that had the most significant effect in induced vertical motion across conditions. Correspondences were also found between motion and both brightness and loudness, providing some evidence of anticipation and reaction to the music. Overall, the proposed analysis techniques provide quantitative data and metrics on the correspondences between micromotion and music, with the EDM stimulus producing the clearest music-induced motion patterns. The analysis and results from this study are compatible with embodied music cognition and sensorimotor synchronization theories, and provide further evidence of the movement inducing effects of groove-related music features and human response to sound stimuli. Further work with larger data sets, and a wider range of stimuli, is necessary to produce conclusive findings on the subject.

Keywords: music-induced motion, sensorimotor synchronization, embodied cognition, movement analysis, motion capture, music information retrieval

Edited by:
Virginia Penhune,
Concordia University, Canada

Reviewed by:
Mats B. Küssner,
Humboldt-Universität zu Berlin, Germany
Frank A. Russo,
Ryerson University, Canada
Maria Witek,
University of Birmingham, United Kingdom

****Correspondence:***
Victor E. Gonzalez-Sanchez
v.e.g.sanchez@imv.uio.no

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1. INTRODUCTION

The intricate relationships between music and human body motion has been of interest to researchers for several decades, but recent technological developments have allowed for more robust and thorough studies, with works focusing on music-induced motion, music performance, and general sensorimotor synchronization (Gritten and King, 2006; Jensenius, 2007; Nusseck and Wanderley, 2009; Maes et al., 2014a; Su, 2016). Moreover, works on sensorimotor synchronization (SMS) have shown what appears to be a predisposition for humans to synchronize motion to periodic stimuli sequences even in the presence of continuous tempo changes (Repp and Su, 2013; van der Steen et al., 2015; Burger et al., 2017).

Many SMS studies have been based on tapping paradigms, but some have exploring other forms of moving in synchrony with external auditory rhythms, such as dance in humans (Keane, 2009; Solberg and Jensenius, 2017b) and synchronization to musical beat in vocal learning animals (Patel et al., 2009; Fitch, 2013). Janata et al. (2012) compiled a series of analysis methods to explore sensorimotor coupling and found that the feeling of being in “the groove” plays a fundamental role in musical appraisal. Furthermore, stimuli with a high level of groove elicit spontaneous rhythmic motion not only from the hands and fingers, but also other body parts such as the head and the legs (Madison, 2006; Kilchenmann and Senn, 2015).

Additionally, body motion related to SMS and groove has been found to follow structured patterns which are often in line with sound-producing actions (Küssner et al., 2014; Godøy et al., 2016).

The concept of embodied cognition assumes that cognitive processes require interactions between the body and its environment (Wilson, 2002). Studies of embodied music cognition propose the need of spontaneous body motion for musical meaning formation and the processing of musical features (Maes et al., 2014b), and a close relationship between spontaneous motion to music and predictions of pulse and rhythmic patterns. This approach to music and motion explains the reflecting and imitating qualities of motion to music as bidirectional processes, where body motion is not only a response to the music stimuli, but also part of the perception mechanism (Todd, 1999; Keller and Rieger, 2009; Witek et al., 2014). Sensorimotor synchronization, then, can be considered as one of the factors involved in this process, with Leman suggesting *embodied attuning* and *empathy* as the other two main components of embodied music cognition (Leman, 2008). It is through such embodied attuning that humans associate musical features such as melody, tonality, or timbre, with motion (Maes et al. 2014a). Empathy, on the other hand, allows for musical features to generate emotion and convey expressions (Wöllner 2012).

Building on the idea of body motion as a means for processing musical information, Phillips-Silver and Trainor (2008) have shown that when people move their body to a certain beat they are more able to interpret ambiguous rhythmic patterns. Moreover, they have demonstrated that body motion does not need to be voluntary to improve music cognitive processes. Participants were rocked on every second and third beat of an ambiguous auditory rhythm pattern while lying passively on a seesaw, and were afterwards asked to interpret the meter of the rhythmic stimuli. A second set of experiments compared passive motion of the head to passive motion of the lower limbs and found that only head motion improved the participants’ rhythm encoding abilities. Based on these two studies the authors suggest that the effect of head motion on rhythm processing is due to the fundamental role of input from the vestibular system, and they further propose an underlying integration of auditory and vestibular inputs in the relationship between motion and auditory metrical rhythm perception.

The acoustic sensitivity of the vestibular system and its role in music cognition has been investigated in studies by Todd (1999), in which he observed that acoustic sequences with varying energy, amplitude, or pulse produce vestibular response signals, which, in turn, can produce a modulated sense of motion. Todd has also proposed a sensory-motor theory based on humans’ experience of rhythm through both a *sensory representation* (of temporal information in the stimulus) and a *motor representation* (of own musculoskeletal system; motor image of the body). In this structure, the spatiotemporal characteristics of an acoustic stimuli are linked to the dynamic characteristics of the motor system, inducing an internal motion representation of the musculoskeletal system, even with actual motion not occurring. According to Todd’s results and observations, the interplay between the vestibular and sensory-motor mechanisms is particularly evident when presented to stimuli with a highly variable range of acoustic features, such as in dance music.

Similarities between sound and motion in musical experience have been studied systematically by Godøy et al. (2016) by exploring the multimodal relations between sound and motion features. Music-related body motion has been generally categorized by the authors as either “sound-producing” or “sound-accompanying,” but with a wide overlap between the two categories. Moreover, the authors suggest that such music-related body motion can also be found in a scale between “quasi-stationary” postures and motion, with the postures serving as orientation points, commonly observed at downbeats and other accented points in the music. Studies by the same authors include a number of quantitative and qualitative analysis methods aimed at establishing correlations between physical sound and motion signals and the subjective perceptions of the related musical experiences. In one of such studies (Nymoen et al., 2013), the authors explore the relationships between sound and motion through a “sound-tracing” experiment in which the subjects moved their hands spontaneously to musical sound. Different sound “contours” (pitch, dynamics, timbre) were used for a correlation analysis with motion features of the participants’ tracings.

Distinct time-varying sound and motion contour features were identified through Spearman correlation and canonical correlation analysis. The correlation coefficients allowed to measure the participants’ temporal accuracy in mimicking the various sound features. The analysis methods proposed by the authors render additional evidence to the ample range of actions that people perform to sounds, and provide a baseline for the identification and classification of music-related motion.

Insight into human gestural descriptions of sound was also found in Caramiaux et al. (2014), with participants exposed to both causal and non-causal sounds, and asked to describe the stimuli through arm and hand gestures. Findings from this study rendered evidence of a fundamental effect of sound source identification in the subsequent gestural description. With causal sounds being generally described mimicking the perceived producing action. In this same line, in Küssner et al. (2014), differences in consistency in gestural representation of sound features were found between trained musicians and untrained participants in real-time exercises. This was particularly evident for pitch, being mostly represented with changes in height, and tempo, being described with changes in hand speed. These movement associations to sound provide initial evidence of consistent bodily responses to particular features, and raises questions over the effect of a wider range of sound characteristics and experimental conditions that have yet to be studied.

Following findings on the influence of rhythmic structures and periodicity on the amount of induced body motion, Burger et al. (2013) investigated relationships between musical features, such as rhythm, timbre, and tempo, with motion characteristics. Pulse clarity, percussiveness, and spectral flux were extracted from a series of stimuli and correlated with a number of free-motion features. Results from this study suggest that whole-body motion seem to be associated with a clear pulse in the music, while spectral flux and percussiveness seemed to have a larger influence on head and upper limb motion. No relationships were observed, however, between tempo and motion features. On the other hand in Styns et al. (2007) synchronization of walking with music was highest around 120 BPM tempo. The potential influence of tempo features on the amount of motion requires further investigation.

Closer to the topic of this paper, Ross et al. (2016) explored music and motion links of people standing still (what they call “quiet” standing) by recording fluctuations in the center of pressure (CoP) of 40 participants listening to music with low and high levels of groove. Events in CoP sway and in the music stimuli were cross-correlated to assess relationships between music and motion, while entrainment was analyzed using spectral coherence. The results suggest that the musical stimuli with a high level of groove produced the least amount of radial sway variability, and the musical experience was observed to influence the amount of postural variability and entrainment. Moreover, high groove was observed to favor entrainment of shorter rhythmic events. Such involuntary entrainment suggests an effect of involuntary musical entrainment on motor and balance control systems, and render additional evidence of involuntary and unconscious motion to music. The study provided additional evidence to factors contributing to the perception of groove, with changes in loudness, pulse clarity, and spectral flux being closely related to changes in perceptual groove. In the present study, an effort is made to further explore which of these—and other groove-related musical features—have the largest effect on motion remains to be fully assessed, as well as the relatively unexplored couplings between non-groove music stimuli and involuntary motion.

In Gandemer et al. (2014), the influence of rotating sound on standing balance was assessed through postural sway recordings from a force platform. Sway amplitude was found to be negatively correlated with the speed of the rotating sound. Subjects exhibited greater stability during fast rotating sound trials, compared to immobilized sound conditions. Although these findings were framed in the context of the role of the auditory system in postural regulation, insight from these results may also suggest the influence of the vestibular system in both sound processing and motion control. Moreover, Coste et al. (2018) found that discrete auditory rhythms have a significant effect in both voluntary and involuntary body sway, with entrainment of sway being higher for tempi at a frequency that was closer to the dominant sway frequency.

In a series of studies aimed at characterizing and understanding music-induced micromotion, Jensenius et al. (2017) investigated how music influences the motion of groups of participants trying to stand still. This micromotion is primarily involuntary and is performed at a scale that is barely observable to the human eye. The study consisted of a statistical comparison of measured motion between music and silent conditions and found that the subjects exhibited a remarkably consistent level of motion when attempting to stand still in silence (Jensenius, 2017). The measured standstill level of a person was shown to be consistent with repeated measures over time. The effects of different musical genres on standstill was measured by comparing Quantity of Motion (QoM) between 7 music excerpts, each with a duration of 20–40 s. The music stimuli were presented in ascending order of rhythmic complexity, starting with slow, non-rhythmical excerpts and ending with acoustic and electronic dance music. The study found significant differences in QoM between the music and silent conditions, with the largest mean QoM occurring during the EDM segment. Moreover, although horizontal motion (medio-lateral and anterior-posterior head sway) was found to account for most of the measured 3-dimensional QoM, vertical motion was shown to have clearer differences between music and silence conditions. These preliminary findings seem to provide additional evidence to findings by Burger et al. (2013) relating to the effects of spectral flux and percussiveness on head and upper limb motion.

In the following, we will describe an exploratory study designed to further characterize human music-related micromotion, with the aim of providing a quantification of the correspondences between music features associated with entrainment and micromotion, while at the same time aiding in the general understanding of sensorimotor theories as a natural manifestation of the internal motor engagement.

2. MATERIALS AND METHODS

2.1. Participants

A total of 71 participants took part in the study (33 female, 38 male, average age: 25 years, SD: 9.5 years) in groups consisting of 3–13 participants at a time[1]. The data collection took place during the University of Oslo "Open Day" in March 2017. The experiment was advertised as "The Norwegian Championship of Standstill" with a NOK 1000 prize for the participant with the lowest recorded motion. Recruitment was open to everyone with no exclusion criteria. Each participant was asked to report on the hours per week spent on the following activities: listening to music (16.8, SD: 12.2), creating music (4.7, SD: 5.3), dancing (1.1, SD: 1.3), and exercising (3.9, SD: 3.7). All participants gave their informed consent prior to the experiment and they were allowed to withdraw from the study at any point in time. The study obtained ethical approval from the Norwegian Center for Research Data (NSD), with the project identification number NSD2457.

2.2. Music Stimuli

The participants were presented with segments of silence and music throughout the 6-min trials. All trials began and ended with 30 s of silence, followed by 5 min of alternating 60-s segments of music and silence. Thus, a complete sequence consisted of: Silence (30 s), Music1 (60 s), Silence (60 s), Music2 (60 s), Silence (60 s), Music3 (60 s), Silence (30 s). The three musical stimuli (played in random order for each group) were excerpts of:

1. Electronic Dance Music (EDM): the "break routine" of the track Icarus (Leclercq 2012). It is an example of a contemporary, energizing dance track with a clear pulse and even rhythmic pattern. This track has also been used in motion capture studies of dancers in Solberg and Jensenius (2017a,b).
2. Classical Indian music: a vocal improvisation by Tejaswinee Kelkar on top of a continuous drone from a shruti box. The track has a slow pulse, and a less clear rhythmic structure. This track has also been used in studies of sound-tracing in Kelkar and Jensenius (2017).
3. Norwegian folk music: a performance of traditional Telespringar dance music played on Hardanger fiddle. This is an example of a piece with an asymmetrical beat pattern, characterized by a long–medium–short duration patter. This track has also been used in studies of rhythmic reference structures (Haugen, 2017).

The tracks were chosen so as to comprise different musical genres and features, and enable the exploration of global musical parameters. **Figure 1** shows waveforms of the samples, to illustrate the dynamic differences of the tracks. The 60-s duration of the stimuli was chosen to allow participants enough time to engage with the music, while keeping the experiment sufficiently short to reduce the effect of tiredness. The sound was played comfortably loud from two Genelec 8020 loudspeakers and a Genelec 7050 sub-woofer.

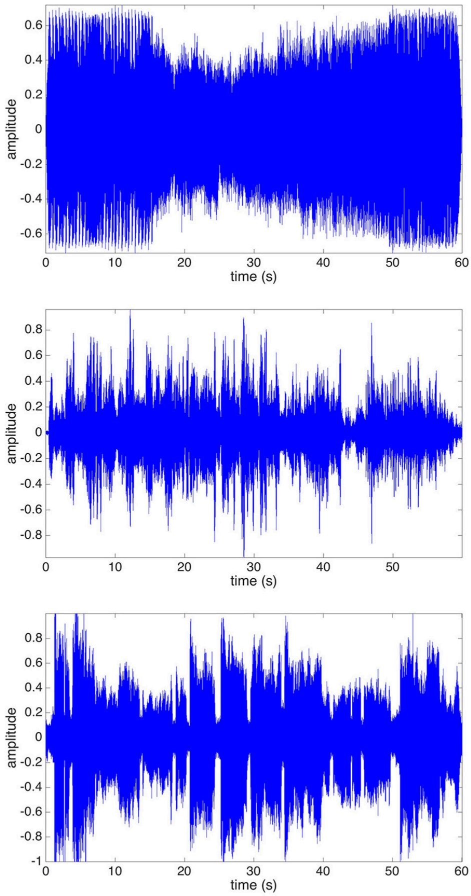

FIGURE 1 | Waveforms of the presented music stimuli: **(Top)** Electronic Dance Music (EDM); **(Middle)** Norwegian fiddle music (Telespringar); **(Bottom)** Indian Classical Music.

2.3. Data Acquisition

The instantaneous position of a reflective marker placed on each participant's head was recorded using a Qualisys infrared motion capture system (13 Oqus 300/500 cameras) running at 200 Hz. Previous studies have shown that the spatial noise level of this motion capture system is considerably lower than that of human standstill (Jensenius et al., 2012). Motion data was recorded and preprocessed in the Qualisys Track Manager (QTM), and the analysis was done in Matlab using the MoCap Toolbox (Burger and Toiviainen, 2013) and custom made scripts.

2.4. Procedure

The participants were recorded in groups of 3–13 people at a time. They were asked to stand as still as possible for 6 minutes, being free to choose their own standing position. The distribution

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[1] Due to the nature of the recruitment, group size was determined by demand and thus, varied as described. Familiarity between participants varied for each group. As described in the following sections, the Group factor was tested as one of the effects in the linear mixed effects model and the result was not significant.

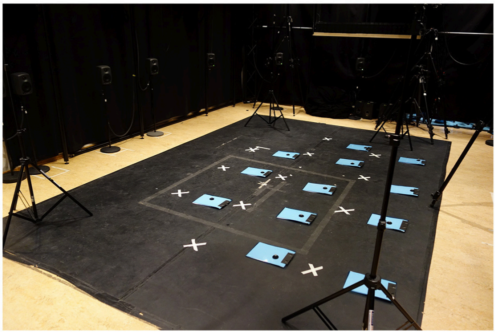

FIGURE 2 | The setup for the experiment in the motion capture laboratory. White marks and questionnaires indicate the position of each participant. Poles with reference markers where placed in each corner of the capture space and used to check the noise-level of the recording (see Jensenius et al., 2012 for a description of the noise-level in optical motion capture systems).

of the participants in the laboratory was standardized across trials, with marks on the floor indicating the approximate feet position (**Figure 2**).

2.5. Quantity of Motion

In order to measure the general standstill level, the *quantity of motion* (QoM) of each head marker was computed as the sum of all the position differences of consecutive samples of the marker, that is, the first derivative of the position time series:

$$QoM = \frac{1}{T} \sum_{n=2}^{N} \parallel p(n) - p(n-1) \parallel$$

where p is either the two-dimensional (Z axis—the vertical plane) or three-dimensional (XYZ axes) position vector of a marker, N is the total number of samples and T is the total duration of the recording. The resulting QoM is measured in millimeters per second (mm/s). Instantaneous quantity of motion was obtained for each participant and for each stimulus.

2.6. Musical Features

To investigate the correspondences between individual musical features and standstill micromotion, we performed computational feature extraction analysis of the presented music stimuli using the MATLAB MIRToolbox (version 1.6.2) (Lartillot et al., 2008a,b). Overall pulse clarity and tempo were obtained for each music stimuli, along with three time-varying frame-decomposed features that have been previously shown to contribute to motor entrainment to music and musical groove (Stupacher et al., 2014; Ross et al., 2016; Burger et al., 2017):

- Loudness: the dynamic envelope of the sound was obtained by calculating the RMS value of the frame-decomposed audio waveform (50 ms frame length).
- Brightness: measured as the spectral centroid of the frame-decomposed audio waveform, that is, the barycenter of the frequency spectrum (50 ms frame length).
- Pulse Clarity: calculated as the rhythmic clarity, indicating the strength of the beats (1 s frame length).

The similarity and correspondences between the sound and motion features were measured by computing cross-correlation between the moving averaged QoM time series (50 ms window length) for every participant and the extracted frame-decomposed musical features. The delay between the sound and motion feature signals was defined as the lag of maximum cross-correlation.

3. RESULTS

3.1. Average Quantity of Motion

The average level of micromotion during the experiment, measured as the QoM of the entire set of participants, was $QoM_{mean} = 8.76$ mm/s. The standard deviation, $QoM_{SD} = 2.20$ mm/s, indicates a fairly low variability among participants. In fact, the extreme measurements across participants were $QoM_{max} = 13.96$ mm/s and $QoM_{min} = 5.98$ mm/s. These findings are in accordance with our previous findings on the general level of micromotion in human standstill (Jensenius et al., 2017).

When comparing the average QoM values to demographics, an independent-samples t-test indicated no significant differences between male and female participants [$t_{(69)} = -1.69$, $p = 0.09$]. Significant correlation was found between QoM and the participants' height, both during music ($r = 0.34$, $p = 0.007$) and during silent conditions ($r = 0.32$, $p = 0.003$), indicating that taller participants tended to move more during the whole experiment. Additionally, age had a significant negative correlation with QoM during the silent segment ($r = -0.23$, $p = 0.034$), while the correlation during the music segment was not significant ($r = -0.17$, $p = 0.087$).

The reported amount of hours per week spent doing physical exercise (group average = 3.9, SD = 3.7), creating music (group average = 4.6, SD = 5.3), and listening to music (group average = 17.2, SD = 12.6) had no significant correlation with measured QoM.

The participants were allowed to choose their standing posture during the experiment. In a post-experiment questionnaire they were asked to report on whether they were standing with their eyes open or closed, and whether they had their knees locked. The majority of the participants reported that they stood with open eyes ($N = 58$ vs. $N = 1$ for closed eyes, and $N = 12$ for those who switched between open and closed eyes during the experiment). Furthermore, 33 of the participants reported standing with locked knees, 23 switched between open and locked knees and 15 reported standing with unlocked knees. Two simple linear regression models were fit to predict QoM based on knee and eye strategy respectively. A significant regression equation was found for knee strategy, with $F_{(1, 68)} = 3.7$, $p = 0.029$, and an R^2 of 0.072. Participants' QoM was approximately 1.31 mm/s smaller when standing with

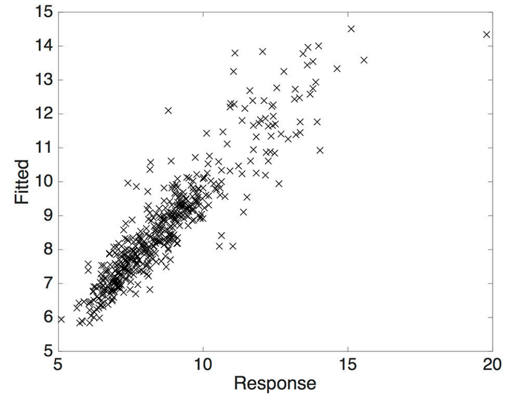

FIGURE 3 | The fitted vs. observed response values from the linear mixed effects model form an almost 45-degree angle indicating a good fit.

unlocked knees than when standing with locked knees. This also fits with previous findings (Jensenius, 2017). The regression equation predicting QoM based on eye strategy was found not significant [$F_{(1,\,68)} = 2.67, p = 0.076, R^2 = 0.046$].

3.2. Influence of Music

The musical influence on the level of standstill was preliminarily assessed by computing the average QoM for the silence vs. music segments. The average for the music condition was $\text{QoM}_{\text{mean}} = 8.83$ mm/s ($\text{QoM}_{\text{SD}} = 1.91$ mm/s), while the average for the silent condition was $\text{QoM}_{\text{mean}} = 8.57$ mm/s ($\text{QoM}_{\text{SD}} = 1.66$ mm/s). A paired-samples (music and silence) t-test revealed that these differences were statistically significant [$t_{(70)} = -2.89, p = 0.003$].

A linear mixed effects model was fit to further analyze the effects of music on QoM. Stimuli was entered as fixed effects (first to last silent segments, EDM, Indian classical, and Telespringar) (**Figure 3**). The model was made of a random slope for by-subject effect of condition (Music or Silence) and a random intercept for Group. P-values were obtained by likelihood ratio tests between the full model (with the fixed effect) and a null model without the effect [$\chi^2{}_{(1)} = 31.143, p < 0.001$]. Bayesian information criterion (BIC) was used as penalized likelihood method for model selection, with smaller BIC number indicating better model adequacy (**Table 1**). Models tested included random slope for by-subject and by-group effect of Stimuli, as well as random intercepts for Subject, Condition, and Position in the capture volume. Random intercepts were also tested through standard deviation and confidence intervals with zero-crossings indicating that position in the lab and condition had no significant effect as random intercepts. The tests of fixed effects showed that EDM ($t = 4.09, p < 0.001$) has a significant effect on a participant's QoM (increasing it by approximately 0.65 mm/s, SE = ±0.16), but the remaining stimuli do not ($p = 0.087$).

3.3. Musical Features

3.3.1. Correspondences With 3-D Motion

Overall, the effect of the musical stimuli on motion seems to correspond with the higher tempo (126 BPM) and total pulse clarity (0.63) of the EDM stimulus, as compared to the other two stimuli (**Table 2**).

To further investigate the effect of musical features on the induced motion, cross-correlation was performed between the three-dimensional QoM measurements and the three sound features described in section 2.6 (loudness, brightness and pulse clarity) for the whole set of participants.

The EDM stimulus was observed to have the largest averaged lag of maximum cross-correlation (delay), at 3.39 ± 1.55 between loudness (measured as the RMS of the amplitude) and QoM. The Indian stimulus produced the smallest cross-correlation at lag −1.43 ± 1.41, indicating a degree of anticipation (**Figure 4A**). Interaction between conditions was assessed through one-way ANOVA with delay between QoM and RMS as dependent variable and music stimuli as independent variable. The effect of the stimuli on the correspondence between QoM and RMS approached significance at the 0.05 level [$F_{(2,\,210)} = 2.64, p = 0.07, \eta_{\text{p}}{}^2 = 0.025$].

The Telespringar condition had the largest averaged lag of maximum cross-correlation between spectral centroid and QoM (2.01 ±1.60), while the Indian condition had the smallest (−0.49 ± 1.48), as shown in **Figure 4B**. The ANOVA showed no statistically significant differences between conditions when comparing correspondence between spectral centroid and QoM [$F_{(2,\,210)} = 0.63, p = 0.53, \eta_{\text{p}}{}^2 = 0.006$].

Additionally, there were no statistically significant differences between conditions when comparing the frame-decomposed pulse clarity with QoM [$F_{(2,\,210)} = 0.20, p = 0.82, \eta_{\text{p}}{}^2 = 0.002$]. The Indian music condition resulted in the largest averaged delay at 1.39 ± 1.27, while the EDM segment had the smallest delay at 0.17 ± 1.45 (**Figure 4C**).

3.3.2. Correspondences With Vertical Motion

In order to investigate whether proposed connections between music features and vertical motion (Rusconi et al., 2006; Eitan et al., 2014) hold true also for the micromotion during standstill, as well as to further explore preliminary findings by Jensenius et al. (2017) on such correspondences, the vertical component of QoM was cross-correlated with frame-decomposed sound features.

The average lag of maximum cross-correlation between RMS and vertical QoM was maximum for the Telespringar music condition at −0.82 ± 1.34, while it was minimum for the EDM segment at −3.76 ± 1.14. The average delay was negative for the three conditions (**Figure 5A**), indicating a level of vertical motion anticipation to RMS events. No statistical significance was found on these differences across conditions at the 0.05 level [$F_{(2,\,210)} = 1.35, p = 0.26, \eta_{\text{p}}{}^2 = 0.013$].

Correspondences between frame-decomposed spectral centroid and vertical QoM was maximum for the Indian music condition at −0.8 ± 1.51, while EDM had the largest anticipation at −4.73 ± 1.63, and all three conditions produced a negative average delay (**Figure 5B**). ANOVA revealed no statistical

TABLE 1 | Bayesian information criterion (BIC) values for the penalized likelihood model selection.

Model ID	Fixed effect	Random slope	Random intercept	BIC
1	Stimuli	by-subject, by-group effect of stimuli	Subject, Group	1844
2	Stimuli	by-subject effect of stimuli	Subject, Group	1679
3	Stimuli	by-group effect of stimuli	Subject, Group	1748
4	Stimuli	by-subject, by-group effect of condition	Subject, Group	1645
5	Stimuli	by-subject effect of condition	Subject, Group	1609
6	Stimuli	by-group effect of condition	Subject, Group	1624
7	Stimuli	by-subject, by-group effect of stimuli	Group	1838
8	Stimuli	by-subject effect of stimuli	Group	1673
9	Stimuli	by-group effect of stimuli	Group	2199
10	Stimuli	by-subject, by-group effect of condition	Group	1639
11	**Stimuli**	**by-subject effect of condition**	**Group**	**1603**
12	Stimuli	by-group effect of condition	Group	2065
13	Stimuli	by-subject, by-group effect of stimuli	Subject	1838
14	Stimuli	by-subject effect of stimuli	Subject	1674
15	Stimuli	by-group effect of stimuli	Subject	1742
16	Stimuli	by-subject, by-group effect of condition	Subject	1639
17	Stimuli	by-subject effect of condition	Subject	1605
18	Stimuli	by-group effect of condition	Subject	1618

Model 11 had the smallest BIC number indicating better model adequacy.

TABLE 2 | Average music and motion features for each of the presented stimuli.

Stimuli	Tempo (bpm)	Pulse clarity	QoM mean (mm/s)	QoM SD (mm/s)
Telespringar	108.63	0.08	8.63	1.82
Indian	53.79	0.04	8.68	2.01
EDM	125.99	0.63	9.19	2.27

significance of the average delay differences between conditions [$F_{(2,\,210)} = 1.84$, $p = 0.16$, ${\eta_p}^2 = 0.017$].

Finally, differences in delay between pulse clarity and vertical QoM were shown significant between conditions [$F_{(2,\,210)} = 9.27$, $p < 0.001$, ${\eta_p}^2 = 0.081$], with the largest negative average delay occurring during the EDM segment at −8.52, while during the Telespringar stimulus the average delay was positive at 0.2 (**Figure 5C**). A Tukey post hoc test revealed that the delay between pulse clarity and vertical QoM was statistically significantly different during the EDM stimulus (−8.52 ± 1.50) when compared with the delay during both the Indian (−2.73 ± 1.46, $p = 0.034$) and the Telespringar (0.2 ± 1.42, $p < 0.001$) stimuli. There was no statistically significant differences between the delay during Telespringar and the delay during Indian music ($p = 0.33$).

4. DISCUSSION

In this study we investigated the influence of music on human motion during standstill. Participants were presented with stimuli alternating between music excerpts and silence in order to determine the effect of music on their micromotion. The computed first derivative of head displacement (used here to represent quantity of motion, QoM) was significantly larger during the music condition, rendering additional evidence to findings from previous studies on music-induced micromotion by Jensenius et al. (2017), where participants were shown to move significantly more while exposed to music than during silent periods. Additionally, the current study expands on Jensenius et al. (2017) by further exploring the correspondences of entrainment-associated musical features with involuntary body motion in the 3-dimensional space and in the vertical plane.

The linear mixed effects model showed that the stimulus with a higher tempo and overall pulse clarity (EDM) produced more involuntary sway from head motion data. This is in line with findings by Ross et al. (2016), in which more motion entrainment to short rhythmical events was observed with increasing levels of groove in the stimuli. Moreover, results from the present study are also comparable to a certain degree with results by Burger et al. (2017), where clear pulses in the music stimuli were shown to correlate with free body movement features. Along with the aforementioned studies, findings from Janata et al. (2012), revealing spontaneous body reaction to high groove music, provide supporting evidence to the greater effect of EDM on involuntary body motion when compared to the other two stimuli.

The analysis of the correspondence between music and motion was performed by computing the delay between 3D and vertical QoM time-series and three frame-decomposed sound features strongly related to music groove perception: RMS, spectral centroid, and pulse clarity. The differences in

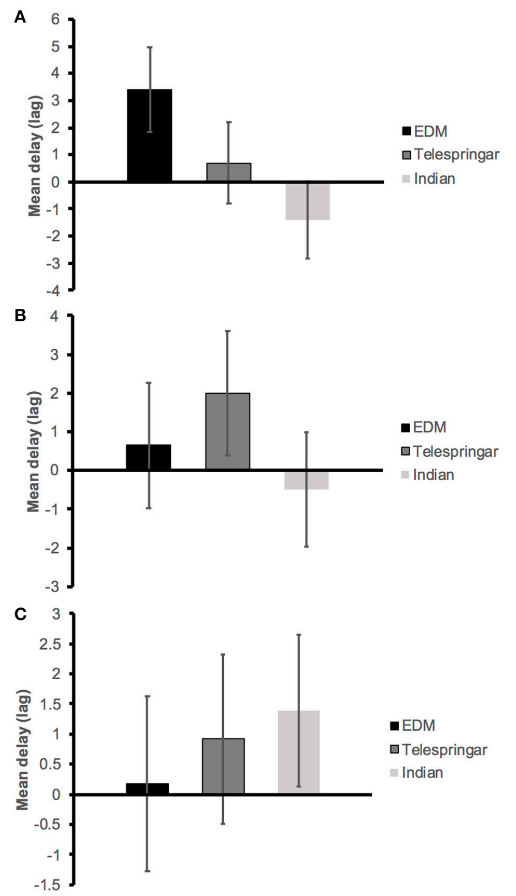

FIGURE 4 | Average lag of maximum cross-correlation (delay) between *three-dimensional* QoM and extracted sound features across participants for each music stimuli. **(A)** Loudness (RMS), **(B)** Spectral centroid, **(C)** Pulse Clarity.

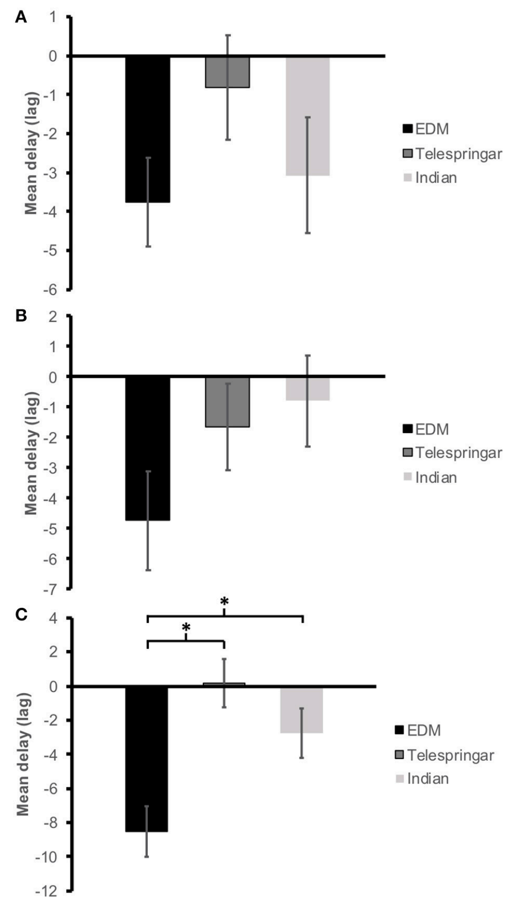

FIGURE 5 | Average lag of maximum cross-correlation (delay) between *vertical* QoM and extracted sound features across participants for each music stimuli. **(A)** Loudness (RMS), **(B)** Spectral centroid, **(C)** Pulse Clarity. Asterisk indicates significant difference at $p < 0.05$.

average delay between the loudness envelope (RMS) and 3D QoM approached significance, while no significant differences were found for the vertical QoM data. Since all the tracks were perceptually normalized in sound level prior to the experiment, the loudness measurement may here be seen as an indication of the "denseness" of the musical material. The EDM condition had the largest delay, while the Indian music condition resulted in a negative delay which may be interpreted as anticipation. The lack of significant results for differences in correspondences between loudness and QoM, despite the range of stimuli that were presented, might suggest RMS has a low contribution to the overall feeling of entrainment.

No significant differences between stimuli were found when analyzing cross-correlation between spectral centroid (brightness) and both 3D and vertical QoM. Delay between spectral centroid and QoM was negative for vertical QoM across all stimuli. The observed negative delay pattern for vertical motion across stimuli could suggest a level of anticipation to perceived brightness events in the music. In line with these results, Nymoen et al. (2013) found negative correlation between vertical sound tracing gestures and spectral centroid, interpreted as a tendency of participants to represent changes in brightness with vertical motion. In the present study, involuntary anticipatory vertical motion to changes in sound brightness could be related to the participants' instantaneous perception of this feature, since there were no differences in motion across the diverse stimuli.

The statistically significant differences in delay between conditions for pulse clarity and vertical QoM can be interpreted as additional evidence to the effect of pulse clarity in music-induced motion. In particular, the anticipatory nature of the vertical motion, as evidenced by a relatively large negative delay during the EDM segment, corresponds with the overall greater pulse clarity of this stimulus when compared to the other two stimuli used in the study. Furthermore, the delay between vertical motion and pulse clarity events for the Telespringar music condition was the smallest, corresponding with the smallest overall pulse clarity of the stimulus. Although no significant delay differences were found between music conditions for 3D motion and pulse clarity, the average delay was positive across stimuli, as opposed to the mostly negative lag of maximum cross-correlation for vertical QoM. The different patterns between vertical and 3D motion across stimuli may be an indication of horizontal motion occurring as a response to pulse clarity events. Such a relationship between pulse clarity and involuntary motion might add to findings by Stupacher et al. (2014), where the wish to move the body to a musical pulse (defined as being "in the groove") was strongly correlated with pulse clarity. Furthermore, in Ross et al. (2016), the involuntary sway of the center of pressure of participants was shown to entrain stronger to stimuli with a higher groove level, characterized by higher spectral flux, density, and pulse clarity.

The results from this study render additional insight into the underlying factors of embodied music cognition, particularly regarding involuntary correspondences between motion and different types of musical stimuli. The findings of correspondences between motion and the loudness envelope, brightness, and pulse clarity are partially in line with results from a number of studies on entrainment (Ross et al., 2016), sensorimotor synchronization (Janata et al., 2012), and the sensation of groove (Stupacher et al., 2014) and could complement such works with the inclusion of the quantification of correspondences to non-rhytmic and "non-groovy" stimuli. Follow-up studies will focus on further exploring the relationship between pulse clarity and vertical motion by testing smaller differences in pulse clarity across stimuli, as well as investigating correspondences with within-stimulus pulse clarity variability.

Capturing only the motion of a participant's head may be seen as a crude representation of a complex bodily interaction with music. The findings, however, proved consistent with our previous results (Jensenius et al., 2017), and also in line with the findings of Phillips-Silver and Trainor (2008), in which the role of the vestibular system in rhythm perception was observed through both passive and active head motion. Further studies on the correspondences between motion and a variety of sound features could contribute to a more robust characterization of the role of head motion for the perception and understanding of sound.

The music excerpts used in the present study were deliberately selected to cover diverse genres and different musical characteristics. Future studies should include other types of genres but also more examples within each genre. It will also be interesting to take into consideration the participants' musical preferences to better assess differences in musical taste, as the propensity to move might be dependent on liking of the stimulus. The extracted musical features used in the present study were selected based on other studies in the field of music-induced motion (Janata et al., 2012; Stupacher et al., 2014; Ross et al., 2016). They do not, however, represent the whole set of music characteristics that could prove relevant for sensorimotor synchronization and embodied cognition. Further work will aim at characterization of a larger set of features across stimuli.

Finally, while the present study focused on temporal characteristics of body motion, it may also be relevant to look at correspondences of music and motion frequencies, along with a wider range of physiological features such as heart rate, breathing patterns, skin conductance, and muscular activity, in order to further characterize involuntary bodily responses to music.

AUTHOR CONTRIBUTIONS

VG-S, AZ, and AJ contributed conception and design of the study. VG-S, AZ, and AJ performed the experiments. VG-S pre-processed the data and performed the statistical analysis. VG-S wrote the first draft of the manuscript. VG-S, AZ, and AJ wrote sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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Paper III

Headphones or speakers? An exploratory study of their effects on spontaneous body movement to rhythmic music

Agata Zelechowska, Victor E. Gonzalez-Sanchez, Bruno Laeng, Alexander Refsum Jensenius

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Headphones or Speakers? An Exploratory Study of Their Effects on Spontaneous Body Movement to Rhythmic Music

Agata Zelechowska[1,2]*, *Victor E. Gonzalez-Sanchez*[1,2], *Bruno Laeng*[1,3] and *Alexander Refsum Jensenius*[1,2]

[1] RITMO Centre for Interdisciplinary Studies in Rhythm, Time and Motion, University of Oslo, Oslo, Norway, [2] Department of Musicology, University of Oslo, Oslo, Norway, [3] Department of Psychology, University of Oslo, Oslo, Norway

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Bruno L. Giordano,
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United States
Mary Broughton,
University of Queensland, Australia

***Correspondence:**
Agata Zelechowska
agata.zelechowska@imv.uio.no

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Previous studies have shown that music may lead to spontaneous body movement, even when people try to stand still. But are spontaneous movement responses to music similar if the stimuli are presented using headphones or speakers? This article presents results from an exploratory study in which 35 participants listened to rhythmic stimuli while standing in a neutral position. The six different stimuli were 45 s each and ranged from a simple pulse to excerpts from electronic dance music (EDM). Each participant listened to all the stimuli using both headphones and speakers. An optical motion capture system was used to calculate their quantity of motion, and a set of questionnaires collected data about music preferences, listening habits, and the experimental sessions. The results show that the participants on average moved more when listening through headphones. The headphones condition was also reported as being more tiresome by the participants. Correlations between participants' demographics, listening habits, and self-reported body motion were observed in both listening conditions. We conclude that the playback method impacts the level of body motion observed when people are listening to music. This should be taken into account when designing embodied music cognition studies.

Keywords: headphones, speakers, playback method, embodiment, music-induced movement, sensorimotor synchronization, motion capture, electronic dance music

1. INTRODUCTION

Thinking about music cognition as a process that happens not only in the mind, but also in the body, is becoming increasingly popular in empirical music research (Leman, 2007). This can be seen in a growing amount of research on music-related body movement, both in performance and perception (Gritten and King, 2006, 2011). Many of the existing studies in the field of embodied music cognition have focused on fairly large-scale body movement, such as, people dancing (Toiviainen et al., 2010; Burger et al., 2013) or walking (Styns et al., 2007; Van Dyck et al., 2015). We have been interested in understanding more about how music may induce body movement also when people try not to move. Using a "standstill" paradigm, we have shown that music may lead to spontaneous body movement, albeit at a very small scale (Jensenius et al., 2017; González Sánchez et al., 2018; González Sánchez et al., 2019). These studies have been done using loudspeakers as the playback method of the music stimuli. Given the small spatial range of the movements we are investigating—most people's head movement is on average around 7 mm/s when standing still—we have asked ourselves whether the playback method has an impact on the result. Past research in speech and music perception has shown that using headphones and speakers can lead to different experimental results. However, as far as we can see there are no studies that have examined the potential impact of such playback technologies on bodily responses to music. Given their distinctive acoustic and psychoacoustic properties, as well as different physical and psychological affordances, one could expect that the use of headphones and speakers would also shape the embodied experience of music. The aim of this article is to explore how headphones and speakers can affect bodily responses to music, and, in particular, spontaneous body movement.

1.1. Headphones vs. Speakers

Initially invented as equipment to be used by telephone operators over 100 years ago, headphones have evolved to become one of today's most popular commercial audio products. There are numerous types of headphones available, such as around-ear, over-ear, in-ear, and conductive. These can again be designed in different ways, for example, with open or closed capsules. To simplify the discussion, all of these will be referred to as "headphones" in this article. We acknowledge that various types (and brands) of headphones impact the final sound in different ways, and deserve a more detailed study in itself. This article, however, will focus on the even larger differences between headphones and speakers.

1.1.1. Main Differences Between Headphones and Speakers

Headphones are an important part of the everyday lives of millions of people around the world. They surpass loudspeakers in terms of their portability, privateness, and affordability. Headphones have become the default playback device for those who enjoy listening to music on the move (walking, running, cycling, etc.), and those who share their acoustic environment with others (shared housing, offices, public transport, etc.). In terms of value for money, high-fidelity headphones are usually more affordable than equally good loudspeaker systems. However, even though headphones have grown in popularity, many people prefer to listen to music on speakers, ranging from small portable mono speakers to high-end multichannel sound systems. Speakers are usually listened to from a distance, which better resembles a natural acoustic environment, and this also prevents the "in-head" feeling associated with sound played through headphones (Stankievech, 2007). Listening on speakers brings the sound alive in the space, and eliminates the problem of "splitting" the sound between the left and right ears, as in the case with headphones. Thus, the spatial representation of sound is different if one listens to the same musical recording on speakers or headphones.

One important bodily difference between headphones and speakers is their visceral impact. Speakers enable sound to be perceived as vibrations in the body, and not only in the ear canal. Such physical sensations are crucial to the perception of low frequencies (McMullin, 2017). Low frequencies, in turn, have a strong impact on the human vestibular system (Todd et al., 2008), which is associated with the sensation of body movement (Todd and Lee, 2015). Furthermore, headphones are typically designed in such way that they block the ear canal or cover the ear lobe, which effectively dampens environmental sounds. This can impair user safety, such as when using headphones in traffic, and can potentially affect postural control. The presence of a continuous auditory input is an important factor in maintaining balance (Gandemer et al., 2016). It has been shown that both soundproof environments and wearing ear defenders significantly increase postural sway in healthy subjects (Kanegaonkar et al., 2012). Similar effects might result from covering the ears with headphones; however, to our knowledge, this has not been systematically investigated. At the same time, there is an indication that noise-canceling headphones, which have an active signal processing unit programmed to cancel sounds from the environment, can disrupt balance. A search of Internet reviews and forums shows that users frequently report experiencing headaches, disorientation, nausea, and dizziness when using such headphones. These are only anecdotal evidence, but there is at least one scientific report of a medical case in which noise-canceling headphones had negative consequences on the vestibular system (Dan-Goor and Samra, 2012).

In addition to the psychoacoustic and physiological differences in users' experience of headphones and speakers, there can also be psychological differences. Headphones may be perceived as a less comfortable playback method, since they have to be worn on the body. Some may perceive the proximity of the sound from headphones as invasive, while others may experience the closeness as intimate (Kallinen and Ravaja, 2007) (this may differ not only from person to person, but also depending on the circumstances and type of music). Last, but not least, there are important social differences between the experience of the two playback methods. Headphones create an isolated "bubble," within which one can listen to music privately. On the contrary, music played over speakers affords a shared experience, whether desired or not. Thus, listening to music on headphones can heighten feelings of introspection, intimacy, or safety (but also isolation). Listening to music on speakers, on the other hand, can lead to heightened social awareness, self-consciousness, and a lack of privacy (but also inclusiveness).

To conclude, the two playback methods have both advantages and disadvantages, and these should be taken into account when designing embodied music cognition experiments.

1.1.2. The Use of Headphones and Speakers in Embodied Music Cognition Studies

To get an overview of how different playback methods are used in embodied music cognition research, we have reviewed some of the experimental studies on body movement to music that were carried out over the past 15 years (**Table 1**). While the sample is not exhaustive, the selected articles provide an overview of various types of music-related body movement: movement synchronization to music, body sway to music, spontaneous dance, and the experience of groove and the urge to move to

TABLE 1 | An overview of some relevant studies on body movement in response to music.

References	Title	*N*	Headphones/Speakers	Loudness
Edworthy and Waring, 2006	The effects of music tempo and loudness level on treadmill exercise	30	Headphones (personal)	2 levels: ~60 and 80 dB
Carrick et al., 2007	Posturographic changes associated with music listening	266	Headphones (earphones)	Not reported
Styns et al., 2007	Walking on music	20	Headphones (Sennheiser HD 62 TV)	Not reported
Forti et al., 2010	The influence of music on static posturography	12	Headphones	Adjusted for participant comfort (range 60–80 dB)
Toiviainen et al., 2010	Embodied meter: Hierarchical eigenmodes in music-induced movement	18	Not reported	Not reported
Van Dyck et al., 2010	The impact of the bass drum on human dance movement	100	Speakers (four Metro MX100, placed in the corners)	Range 70-90 dB depending on point in time, average level not reported
Demos et al., 2012	Rocking to the beat: Effects of music and partner's movements on spontaneous interpersonal coordination	48	Not reported	Not reported
Burger et al., 2013	Influences of rhythm and timbre-related musical features on characteristics of music-induced movement	60	Speakers (two Genelec 8030A)	Not reported
Kilchenmann and Senn, 2015	Microtiming in Swing and Funk affects the body movement behavior of music expert listeners	160	Headphones (AKG 271 MkII)	Playback loudness was adjusted
Pagnacco et al., 2015	Effect of tone-based sound stimulation on balance performance of normal subjects: Preliminary investigation	39	Headphones (high-fidelity)	Adjusted for participant comfort
Van Dyck et al., 2015	Spontaneous entrainment of running cadence to music tempo	16	Headphones (Sennheiser HD60 with Sennheiser HDR130 audio transmitter)	Not reported
Ross et al., 2016	Influence of musical groove on postural sway	40	Headphones (noise-minimizing)	Adjusted for participant comfort
Witek et al., 2017	Syncopation affects free body–movement in musical groove	25	Speakers	75 dB
Burger et al., 2018	Synchronization to metrical levels in music depends on low-frequency spectral components and tempo	30	Speakers (two Genelec 8030A)	Not reported
Coste et al., 2018	Standing or swaying to the beat: Discrete auditory rhythms entrain stance and promote postural coordination stability	20	Headphones (wireless earphones)	Adjusted for participant comfort
Etani et al., 2018	Optimal tempo for groove: Its relation to directions of body movement and Japanese nori	38	Speaker (one Genelec 8050A)	Not reported

The original information about the types of headphones or speakers given by the authors is shown in parentheses. The studies are listed in a chronological order.

music. Contrary to our expectation, most of the reviewed studies used headphones as playback method. This surprised us, since we thought that research on human body movement would use speakers to allow for free movement in space. When it comes to the quality of the equipment used, it ranges from basic consumer products (e.g., Sennheiser HD 62 TV headphones) to professional equipment (e.g., Sennheiser HD60 or AKG 271 MkII headphones). In several of the studies, however, the specific brand and model are not reported, and information on the type of headphones used is also missing. The level of detail in reporting on speaker type and brand is equally varied. Some of the studies use a pair of stereo speakers, some use only one speaker, while others are based on a multi-channel speaker setup. Those that have mentioned the speaker brand use studio quality equipment (most often different types of Genelec speakers), but one article does not report on speaker brand and type.

Besides the type and brand of equipment used, the playback level is an important sound factor to consider when designing an embodied music cognition experiment (Todd and Cody, 2000). **Table 1** therefore also includes the reported sound level (if any) in the selected studies. It turns out that several articles do not report the sound level at all, while others report it as "comfortable." In the cases where measurements are provided, the sound levels are typically in the range of 60–90 dB. It should be mentioned, however, that measuring sound levels in an experimental setting is not straightforward. This is particularly true for headphones, for which a proper sound level measurement would involve a dummy head and calibrated microphones to get reliable results.

There are often pragmatic reasons for choosing a particular playback method over another for an experiment. In some cases, a laboratory is already equipped with a particular sound playback system. Other times, the experimental design may dictate the type of equipment to use. For example, while studying free movement to music—such as dancing—it is impractical to use wired headphones. Then, a speaker-based setup would be the most viable solution, although wireless headphones could also be considered. Also, some experimental rooms may have challenging acoustics and/or problems with leaking sounds to adjacent rooms. In such cases, headphones may provide a better overall setup for an experiment. While such reasons often legitimize the choice of a particular playback system, our small review shows that these choices are rarely described and discussed.

1.1.3. Comparative Studies of Headphones and Speakers

Many of the previous studies on differences between headphones and speakers have been carried out in the fields of acoustics and sound engineering. In such studies, the focus is typically on the technical design of the equipment and the reproduced signal quality. We are more interested in the experiential differences between headphones and speakers, and thus, studies in, for example, speech science, are more relevant. One such study is that of Schmidt-Nielsen and Everett (1982), who found that mild fluctuations of pitch in synthetic vowels were more easily detected when the stimulus was presented using speakers instead of headphones. Another relevant field is traffic safety. In a study on the efficiency of simulated driving during music listening, Nelson and Nilsson (1990) showed that participants' reaction times for shifting gears were longer when using headphones than when using speakers. Interestingly, they also found that the subjective fatigue was the same in both conditions.

In a mixed-methods study, Kallinen and Ravaja (2007) compared the experience of listening to business news through headphones and speakers. Here, different types of physiological measures were collected: facial electromyography (EMG), pulse transit time (PTT), respiratory sinus arrhythmia (RSA), and electrodermal activity (EDA). They found that listening to news using headphones elicited more positive reactions (EMG activity of zygomaticus major) and higher attention (shorter PTT) compared with the use of speakers. Headphones listening was also preferred by most of the participants. However, while listening to speakers, participants who scored high on the sociability and activity personality scales showed increased attention (lower RSA), whereas impulsive, sensation-seeking participants showed higher physiological arousal (increased EDA). This study showed not only crucial differences in reception of speech from headphones and from speakers, but also that these differences can vary between people depending on their personality traits. Some years later, Lieberman et al. (2016) conducted a similar study, comparing the effects of headphones vs. speakers on how participants received emotional stories (personal confessions and requests for help). The authors found that listening to such stories through headphones increased the participants' feeling of the narrator's presence, their subjective immersion in the story, and their positive attitude toward the narrator, compared to when they listened to the same stories from speakers. Headphones listening also increased the participants' willingness to donate money. The authors conclude that listening to speech on headphones reduces felt social distance.

In the field of music perception, Koehl et al. (2011) investigated whether headphones can be used on equal terms with speakers in studies where listeners have to assess subtle differences between auditory sequences. In their study, expert listeners were asked to rate (by degree of similarity and personal preference) pairs of short baroque sonata excerpts while listening from headphones or from speakers. The stimuli had been recorded with two different microphone setups. The study revealed that the participants could distinguish the types of recordings equally well while listening to headphones or speakers, but the preference for one type of recording was slightly but significantly higher in the headphones condition. Furthermore, evaluating the excerpts through headphones resulted in greater consistency across participants. The authors attributed this difference to the fact that while listening to speakers, the participants could freely move their heads, which modifies the reception of sound. The headphones, on the other hand, were fastened on the participants' heads, which provided a stereo field independent of head movement. Despite these observed differences, Koehl et al. (2011) concluded that both playback methods are equally appropriate for studies in which listeners evaluate and rate musical excerpts.

Confirming common knowledge among audio engineers, King et al. (2013) showed that highly trained recording engineers and music producers worked differently while monitoring with either headphones or speakers. This was observed in how they set levels to balance solo musical elements against a backing track. The authors concluded that results from tests that used headphones as a playback method might not be generalized to situations where speakers are used, and vice versa.

One part of a music experience that differs significantly between headphones and speakers, is the perception of low frequencies. McMullin (2017) explored differences in loudness and bass level preferences while listening through the two types of devices. When asked to equalize sound parameters and adjust to a preferred sound level, the listeners set the loudness level 2 dB higher and the bass level 1 dB higher for the loudspeakers. Moreover, the variance in preferred bass and loudness levels was comparatively greater in the headphones condition. Interestingly, adjusting the bass level proved much more difficult with headphones than with loudspeakers. McMullin (2017) points out that listening on headphones deprives the person of whole body sensations of low frequency vibrations. This means that listeners have less tactile feedback to help them make decisions about the right bass level in music. Additionally, this study demonstrated that trained listeners were more consistent than untrained listeners in their bass level and sound volume level adjustments.

Another group of researchers discussed auditory experiments conducted remotely over the Internet, where researchers have little control over playback methods available to participants (Woods et al., 2017). They argued that headphones, which attenuate external noise and generally improve control over the basic quality of the presented stimulus, should be the preferred method of presenting sound. To verify the type of playback system participants are using, the researchers developed a short test of pure tones that are heard differently through headphones and speakers due to phase cancellation. While this study does not explicitly compare headphones and speakers, it supports the argument of treating them as unequal playback methods in experimental research.

To conclude, our review of studies comparing the experience of using headphones and speakers showed various differences between the two playback methods. Such studies typically focus on either speech or music perception. None of them, however, directly address bodily responses to music.

1.2. Body Movement as a Spontaneous Response to Music

There is a general belief that "music makes us move," but the empirical evidence of such a claim is scarce. Many of the studies on music-related movement focus on voluntary and fairly large-scale displacements of the body (Gritten and King, 2006, 2011). When it comes to spontaneous responses to music, it is more relevant to consider the literature on postural sway (Forti et al., 2010; Ross et al., 2016; Coste et al., 2018) and subtle head nodding and tapping (Hurley et al., 2014; Kilchenmann and Senn, 2015).

1.2.1. Music-Related Micromotion

Our main focus is on spontaneous, voluntary or involuntary movement of the body that occurs while experiencing music, what we call *micromotion*. We have studied micromotion using an experimental paradigm in which subjects are asked to stand still on the floor while listening to music (Jensenius et al., 2017). From these studies we have found that people's micromotion is on average higher when listening to music than when they stand still in silence, even when they deliberately try not to move (Jensenius et al., 2017; González Sánchez et al., 2018; González Sánchez et al., 2019). Different types of music seem to influence the micromotion in various ways. We have, for example, found that music with a clear pulse and rhythmic structure (such as found in electronic dance music, EDM) leads to higher levels of micromotion. This can be attributed to a number of factors—for instance, intensified breathing, body sway, or postural adjustments.

Our findings on micromotion are consistent with studies of physiological responses, suggesting that the experience of music can be reflected in various changes in human hormonal, cardiovascular, respiratory, thermoregulatory, muscular, and even digestive systems (Hodges, 2009). As Hodges points out, these physiological responses may also lead to physical responses to music in the form of body movement. Micromotion can also signify an ongoing rhythmic entrainment process (Large and Jones, 1999), which is demonstrated in periodic motion of the body synchronized to the beat of the music. A recent overview of studies concerning this phenomenon can be found in Levitin et al. (2018).

1.2.2. Spontaneous Movement to Music

While our previous studies have been on music-related micromotion, the current experiment focused on slightly larger-scale movement. This could be in the form of head nodding or finger tapping, or other subtle body movement that spontaneously appears in response to music. Reviewing the literature, we see that some researchers use "spontaneous movement to music" to describe free, dance-like movement that participants are asked to perform (Luck et al., 2009; Toiviainen et al., 2010; Burger et al., 2013). Here, we focus on *spontaneously appearing* movement, that is, when participants are not instructed to move, or when they are instructed to move a different body part.

In an experiment on "attentive listening," Kilchenmann and Senn (2015) investigated listeners' spontaneous body motion. They observed that participants spontaneously moved their heads to the beat of the music when they were asked to rate excerpts of swing and funk music with minute timing manipulations. This happened even though they were not given instructions to move, and they were not aware that their movements were being measured. Participants who identified as musicians reacted more strongly to the sonic manipulations, which was reflected in the intensity of their head movement. Hurley et al. (2014) took a different approach to measuring spontaneous body movement to music. They equipped participants with a drum pad and told them to tap to the music, if they wished. Apart from tapping data, they also recorded head motion, although no instructions about performing head movements were given to participants. Spontaneous motion synchronization to music was treated as a proxy for the participants' engagement, together with their ratings of the *groove* of the music, that is, the aspect of music that elicits an urge to move (Janata et al., 2012). The researchers found that music with "staggered" instrument entrances—that is, instruments entering one at a time, as opposed to simultaneously—elicited increased sensorimotor coupling. Furthermore, the musically trained participants were more eager to tap along with the music, and their timing was more accurate. However, the precision with which the participants synchronized their head movements to the music did not differ between the musically trained and untrained participants.

Another set of studies that have yielded interesting findings with regards to the effect of music on spontaneous body motion, is in the field of *posturography*. Here, postural control is studied when people stand upright in either static or dynamic conditions. In posturography studies the auditory stimuli are treated as external distractors that can affect the participants' balance. Ross et al. (2016) found that listening to music with high levels of groove reduced the radial body sway when standing. At the same time, it encouraged spontaneous motor entrainment to rhythmic events in the music without any instruction for such movement. Coste et al. (2018) demonstrated that discrete auditory rhythms can influence both voluntary and involuntary body sway, and induce movement entrainment to rhythm, especially when the rhythmic frequency is similar to the body's natural sway.

Although the correspondences between music and body movement are not yet fully understood, a number of theories have been proposed to explain why people often spontaneously start moving to music. One line of research highlights the existence of robust connections between the auditory and motor areas in the human brain (Zatorre et al., 2007), and the automatic activation of movement-related structures, such as the supplementary motor area, premotor cortex, and cerebellum, in response to auditory rhythms (Grahn and Rowe, 2009). This suggests that, at least to some extent, body movement can happen automatically, as a spontaneous, and perhaps even involuntary, response to music. Moreover, moving to music is universal among humans (Blacking, 1995), and people in all known cultures dance to music (Sievers et al., 2013). Indeed, many studies explain the phenomenon of moving to music from an evolutionary perspective, showing that the strong connections between sound and body movement are deeply rooted in human biology and culture (Levitin et al., 2018). Some researchers suggest that the synchronization of body movements to music was evolutionarily reinforced, because it promotes interpersonal cooperation and bonding (Reddish et al., 2013; Tarr et al., 2016). This may be a reason that moving to music—with or without other people—is strongly linked with pleasure (Solberg and Jensenius, 2017; Witek et al., 2017).

1.2.3. The Effect of Musical Stimuli

While many musical features can potentially lead to spontaneous movement of the body, there is growing evidence that rhythmic elements may be particularly movement-inducing (Burger et al., 2013). That is probably the reason why many researchers tend to use music genres with clear rhythmic structures when studying music-related body movement. Several recent studies have focused on the genre of EDM (Moelants, 2003; Solberg and Jensenius, 2017; Burger and Toiviainen, 2018), which may also be seen as reflecting the uptake of this particular genre in a large part of today's popular music. Also in our own previous studies we have found that EDM makes people move more than other musical genres (Jensenius et al., 2017; González Sánchez et al., 2018).

There is, however, no consensus on how complex the music and its rhythmical structure should be in order to create the urge to move or to aid in movement synchronization. This topic has been explored in the context of rehabilitation of patients with diseases that affect their motor control (such as Parkinson's or Huntington's disease), but with no clear conclusions (Wittwer et al., 2013). Witek et al. (2014) argue that the rhythm should be neither too simple nor too complex. Styns et al. (2007) showed that people synchronize their walking cadence better with complex music than with simple rhythmic structures. It has also been suggested that the subjective enjoyment of a piece of music strongly influences the feeling of groove (Janata et al., 2012; Senn et al., 2018).

1.2.4. The Effect of Individual Differences

In our previous studies we have found that time spent on physical exercise positively correlates with the amount of involuntary movement during standstill (Jensenius et al., 2017). We have also found a correlation with age, showing that younger people tend to move more than older people when trying to stand as still as possible (Jensenius et al., 2017; González Sánchez et al., 2018). Moreover, we observed positive correlations between body height and quantity of motion (González Sánchez et al., 2018). This is similar to results by Dahl et al. (2014), who found that the preferred tempo for dancing can be predicted by the height and leg length of the participants. This suggests that body morphology may influence the process of physically engaging with music.

As we have shown in sections 1.1.1 and 1.1.3, there are differences in preferred use for headphones and speakers. These differences might depend on the listening context, but also on the listener. For example, headphones are used more often by young adults than those who are above 45 years old (Fung et al., 2013). Having a broader understanding of the listeners' preferences and habits for using headphones and speakers could aid understanding their responses to music listened through these playback methods. To our knowledge, there are yet no studies on this topic.

1.2.5. Movement Measures

Previous studies on body movement to music have investigated different body segments (Luck et al., 2010; Burger et al., 2013), movements of the head (Hurley et al., 2014; Kilchenmann and Senn, 2015; González Sánchez et al., 2018; González Sánchez et al., 2019), and Center of Mass (CoM) or Center of Pressure (CoP) (Burger et al., 2013; Ross et al., 2016). In posturography studies, CoM is one of the most widely used measures of postural stability (Winter, 2009). In music cognition research, however, there are no standard movement measures. In the present study, we analyzed three different measures: Head Motion (Head), Center of Mass (CoM), and Whole Body Motion (Body). The latter was calculated as an average of all markers (see below for details). We used these three measures in order to explore different kinds of movement responses to music. Additionally, each of these three movement measures is in a different way sensitive to postural adjustments and incidental fidgeting.

1.3. Research Questions and Hypotheses

In sum, there is some scientific evidence of differences between headphones and speakers in listening experience. There is also a growing body of literature on spontaneous body movement to music. However, to our knowledge, there has been no previous studies on the combination of these two topics: influence of playback method on spontaneous movement to music. Based on the above literature review, and our own previous findings, we therefore ask the following questions:

1. Will different playback methods (headphones and speakers) influence the quantity of observed spontaneous movement when people stand and listen to music?
2. Can any differences in observed movement be related to the musical complexity of the sound stimuli?
3. Can any differences in observed movement be related to the individual (demographics, musical preferences, and listening habits)?

Although previous knowledge is limited, we hypothesize that the playback method (headphones or speakers) will result in different spontaneous bodily reactions to the music. Given the exploratory nature of the study, and the lack of previous research on the topic, we do not have a prediction for the direction of the difference in movement. When it comes to the question of musical complexity, we hypothesize that a higher degree of musical complexity (with a particular focus on rhythmic complexity) will lead to a higher level of movement. The question of individual differences is exploratory, and we therefore do not have hypotheses for this question.

2. METHOD

The main objective of this study is to examine possible relationships between sound playback methods and spontaneous body movement. For that reason we designed a motion capture experiment in which participants listened to the same stimuli with both headphones and speakers. The study was constructed around a 2 × 2 × 3 ANOVA design: playback method × stimuli complexity × movement measure. In addition, we wanted to explore possible correlations between observed body movement and individual differences between participants. The study obtained ethical approval from the Norwegian Centre for Research Data (NSD), under the project identification number 58546.

2.1. Participants

A total of 42 participants were recruited to take part in the study via advertisements placed in several locations around the University of Oslo. The exclusion criteria included hearing loss, neurological disorders, arthritis, orthopedic conditions, recent injury, and balance disorders. A total of 5 participants were excluded from the analysis due to data loss, a misunderstanding of the instructions, and one late report of injury. Two more participants were excluded as outliers, because their quantity of motion exceeded 3 standard deviations (SD). Subsequently, 35 participants were included in the analyses (18 females and 17 males; average age: 27.1 years; SD: 5.4 years; average height: 176.3 cm; SD: 9.7 cm). The height was calculated as the mean value of each participant's vertical head position. Of the included participants, 24 reported that they had some musical training, either professional or self-taught, out of which 19 still regularly played an instrument or sang. All the participants were rewarded with a gift card worth NOK 200 (approximately EUR 20).

2.2. Music Stimuli

Based on findings from previous studies (Jensenius et al., 2017; González Sánchez et al., 2018; González Sánchez et al., 2019), we decided to focus on using EDM-like tracks in the present study. This is a musical genre that is designed specifically for making people want to dance, and is characterized by a flat-four rhythmic pattern and a synthesizer-based melody and accompaniment (Solberg and Jensenius, 2017). We believe that it is important to study the effects of "real" music, so four of the six selected tracks were taken from commercially available EDM tracks. Two custom-made control tracks were also included in the list of stimuli (the six tracks are described below, and details are provided in **Table 2**).

The different tracks were selected because they have different levels of *musical complexity*. Musical complexity is here used to explain the combination of vertical and horizontal elements. The vertical elements include harmonic (combinations of individual tones), timbral (the sound of individual instruments), and textural (combinations of instruments) features. These vertical elements relate to the sonic "layers" of the music. EDM is to a large extent based on a combination of synthesized sounds and processed instrumental samples, and the different vertical layers often fuse into a complex texture in which it is not entirely straightforward to identify individual instruments or harmonic content (Brøvig-Hanssen and Danielsen, 2016). The horizontal (temporal) elements of EDM are based on its characteristic "flat-four" bass drum pattern, which drives the experience of a clear pulse of the music. On top of such a bass pattern there are often various layers of micro-rhythmic structures, as well as melodic lines. While seemingly simple in structure, the final "sound" of an EDM track is often composed of a large number of horizontal and vertical layers. It is characterized by a repetitive pattern, but often it is the micro-rhythmic *variation* that brings the music to life (Danielsen, 2010; Danielsen et al., 2019).

To reduce the number of independent variables, we decided to select EDM tracks that would allow for comparing the *rhythmic complexity* between stimuli in a systematic manner. By rhythmic complexity we here refer to the number of elements contributing to the rhythmic structure. All of the chosen stimuli have a clear pulse, but they have an increasing number of rhythmic elements that contribute to the overall rhythmic complexity. For example, a plain metronome can be considered to have a low level of rhythmic complexity, while an elaborate EDM track will have a high level of rhythmic complexity. Only tracks without lyrics were selected, to focus on the non-verbal content of the music. The six selected stimuli were:

1. *Metronome*: A plain metronome track based on a synthesized "EDM-style" drum sample.
2. *Rhythm*: A simple two-measure drum pattern adapted from the study by Honing et al. (2012). This was produced

TABLE 2 | An overview of the music stimuli used in the current study.

Artist	Song title/Label/Year	Duration (s)	Tempo (BPM)	Event density
—	Drum metronome	45	120	95
—	Two-measure drum pattern	45	120	115
André Bratten	Trommer og bass/Correspondant/2014	0:00–0:45	120	206
Neelix	Cherokee (Extended Mix)/Kontor Records/2017	4:32–5:17	138	253
Neelix	Cherokee (Extended Mix)/Kontor Records/2017	1:07–1:52	138	278
Pysh feat. Poludnice	Sadom (Original Mix)/Mono. Noise/2017	0:28–1:13	123	297

The durations of the EDM stimuli refer to the extracted segments from the original tracks.

using the same synthesized drum sample as used in the metronome track.

3. *Bratten*: An excerpt from the beginning of the song *Trommer og bass* by André Bratten. This was chosen as an example of a professionally produced EDM track with a low level of complexity. It consists of a basic, steady rhythm, and no melody. Thus, it resembles the Rhythm track, but with richer and more interesting sonic qualities.
4. *Neelix1*: This is an excerpt from the trance track *Cherokee* by Neelix. It contains a complex rhythmic structure, including micro-rhythmic features, as well as several layers of bass and melody lines.
5. *Neelix2*: This is an excerpt from a different part of the same track as Neelix1. The main difference is that this track contains a small "break routine," with a build-up of rhythmic layers and an upwards moving glissando.
6. *Pysh*: This is an excerpt from the deep house track *Sadom* by Pysh. It is based on a steady, but slightly laid-back beat, consisting of samples of acoustic drums. The use of a sampled voice (but no lyrics) also makes it perceptually different from the other tracks.

To summarize, three of the tracks were primarily rhythmic in nature (Metronome, Rhythm, Bratten), yet with an increasing level of rhythmic complexity. The three other tracks had even more rhythmic complexity, but also contained more melodic layers. The increased complexity can be seen in the amplitude plots (**Figure 1**) and spectrograms and (**Figure 2**) of the sound files. Each track was ∼45 s in duration (cut to match the bars), with small fade-ins and fade-outs for the excerpts that were cut from original EDM tracks. All the stimuli were in quadruple meter, contained no lyrics, and the tempo varied from 120 to 138 BPM. The tracks were created/modified in the Reaper digital audio workstation.

During the experiment, each of the six music stimuli were played in random order. The sound tracks alternated with 30-s segments of silence, and there were also silence segments in the beginning and end of the experiment. The total duration of the experiment was ∼8 min. Since the tracks differed so much in their musical content, it was not possible to do a signal-based normalization of the loudness level. Therefore, the loudness level of each track was adjusted by ear by three of the authors during the pilot phase. This was done by listening to pairs of tracks, and adjusting the levels of each pair until the three listeners agreed that the perceptual sound level of the tracks was similar. The same procedure was used to adjust the levels between speakers and headphones. That is, three of the authors listened to each track with both playback methods, and adjusted the levels until they matched perceptually. The consistency of the perceived loudness level between playback methods and between tracks was validated by the participants of a pilot study conducted prior to the experiment.

2.3. Apparatus

The motion capture data collection was done using 20 reflective markers attached to relevant anatomical landmarks on the body of the participants (**Figure 3**). An infrared optical marker-based motion capture system from Qualisys (12 Oqus cameras) was used in the study, running at a 200 Hz sampling rate. The data was recorded and pre-processed in Qualisys Track Manager, and exported as TSV files for further analysis.

The sound stimuli were played from a laptop running a custom-built patch developed in Max by Cycling '74. This patch ran the stimuli in randomized order, and was also set up to synchronize with the motion capture system. All the sound stimuli were played from uncompressed audio files (.WAV), using an RME MADIface Pro sound card. The headphones used in the experiment were a pair of Beyerdynamic DT 770 PRO 80 Ohm; they were carefully placed on the participant's head and the headband was adjusted for their comfort. The speakers were a pair of Genelec 8020 loudspeakers with a Genelec 7050 subwoofer. The speakers were placed in a triangle configuration, each at a distance of 315 cm from the participant. They were mounted on a stand at a height of 165 cm, and with a distance of 290 cm between speakers. The subwoofer was placed on the floor equidistant between the speakers, and 245 cm away from the participant. The sound level of both playback systems was set to a level that was loud, but not uncomfortable. The sound level was set to 72 dB for the speakers and 74 dB for headphones. The difference was based on the perceptual matching done prior to the experiment (see above). The difference in 2 dB was also applied in McMullin (2017), to compensate for a lack of cross-talk in headphones condition. To determine that the sound level was indeed loud but not uncomfortable, a short sound check was done prior to the headphones session. A total of eight participants asked for lowering the sound level (to either 72 or 68 dB).

2.4. Questionnaire Measures

The participants were asked to fill in a short questionnaire after each of the two listening sessions (headphones and speakers). These included questions about felt movement, tiredness, and the perceived loudness (**Table 3**). At the end of the experiment, the participants filled in a longer questionnaire on demographics and listening habits (such as frequency of using headphones and speakers, see **Table 4**), and a Short Test of Music Preferences (STOMP; Rentfrow and Gosling, 2003). They were also presented with short excerpts of the music stimuli, and asked to evaluate how much they liked listening to them during the experiment. Three additional questionnaires, which are not a part of the current analysis, were filled in between the listening sessions and as a part of the final questionnaire.

2.5. Procedure

The experiment took place in the fourMs Lab at the University of Oslo between April and May 2018. The participants were invited to the laboratory individually and were asked to give written consent before the study began. Afterwards, the participants were instrumented for the first listening session, which was headphones listening for one half, and speakers listening for another half of the participants. Each group was presented with the same set of stimuli in a randomized order. Participants

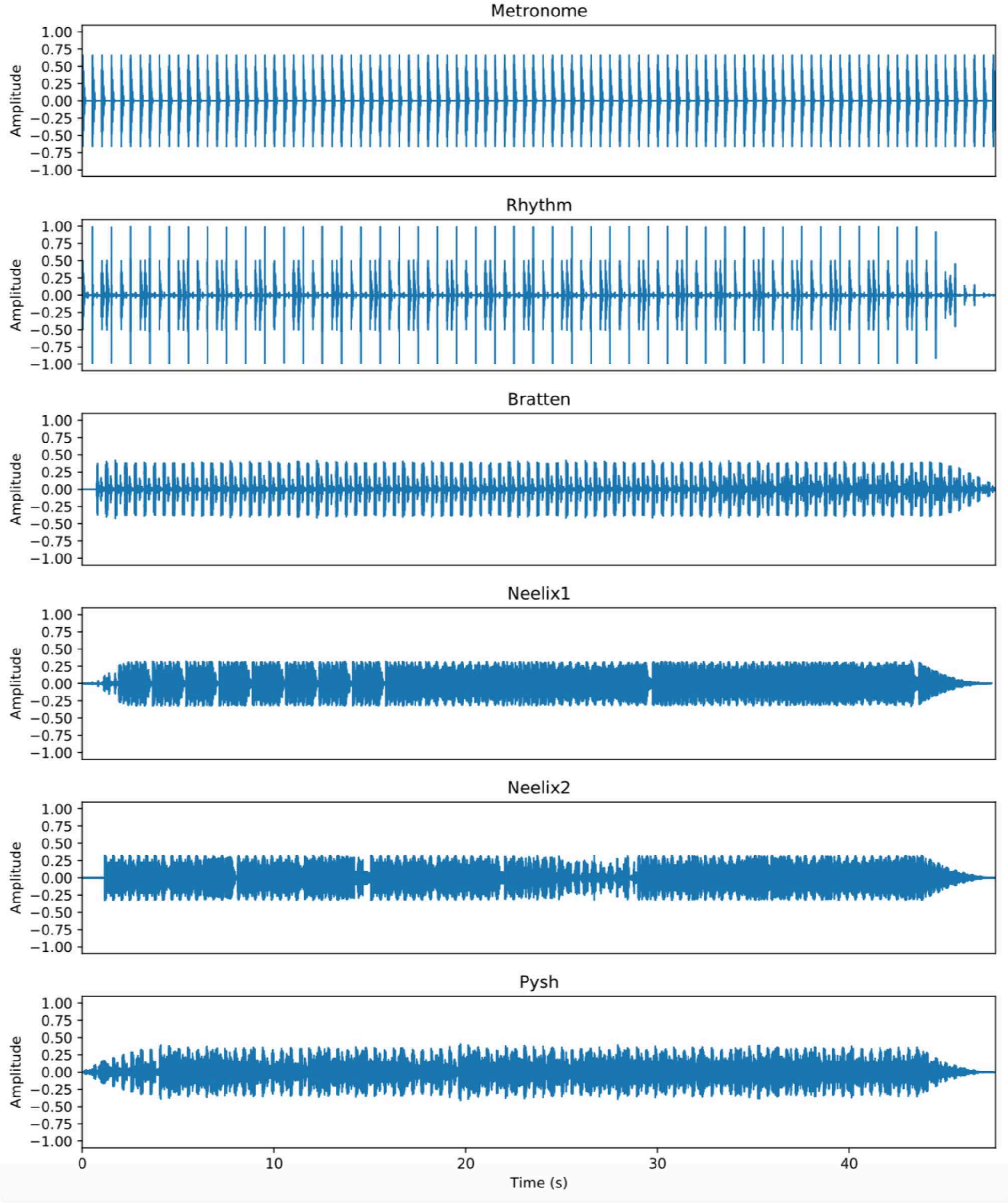

FIGURE 1 | Waveform displays of the six sound stimuli show the increasing level of musical complexity from top to bottom (Metronome = low complexity, Pysh = high complexity). The amplitude peaks of the Metronome and Rhythm tracks are higher than those of the four EDM tracks, but they contain much less energy between the beats. The tracks were judged to be perceptually similar in loudness (see text for details).

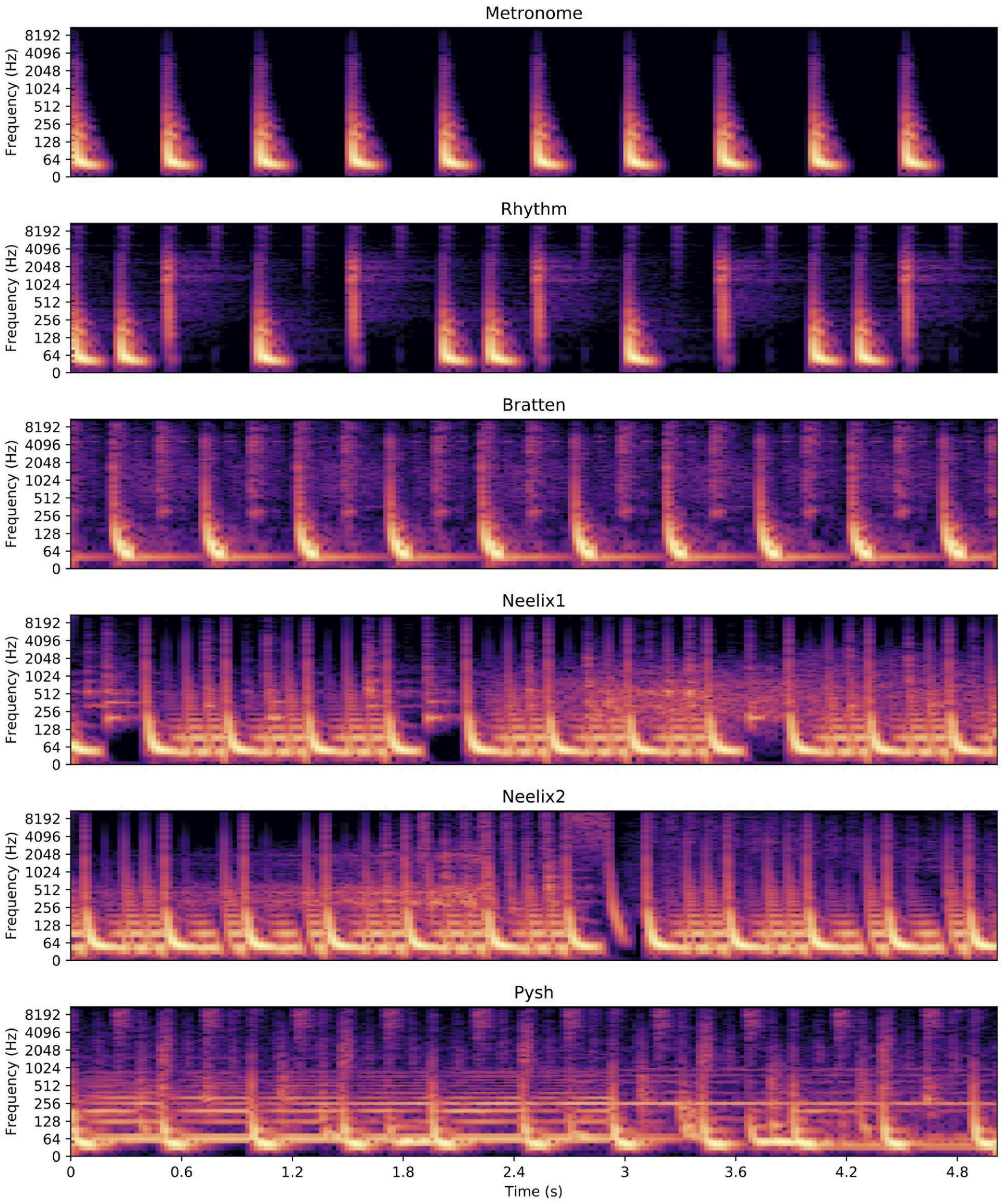

FIGURE 2 | Spectrograms of 5 s of each of the six sound stimuli. These close-ups reveal the differences in musical complexity between the different tracks: low for the metronome (top) and higher for the EDM tracks (bottom).

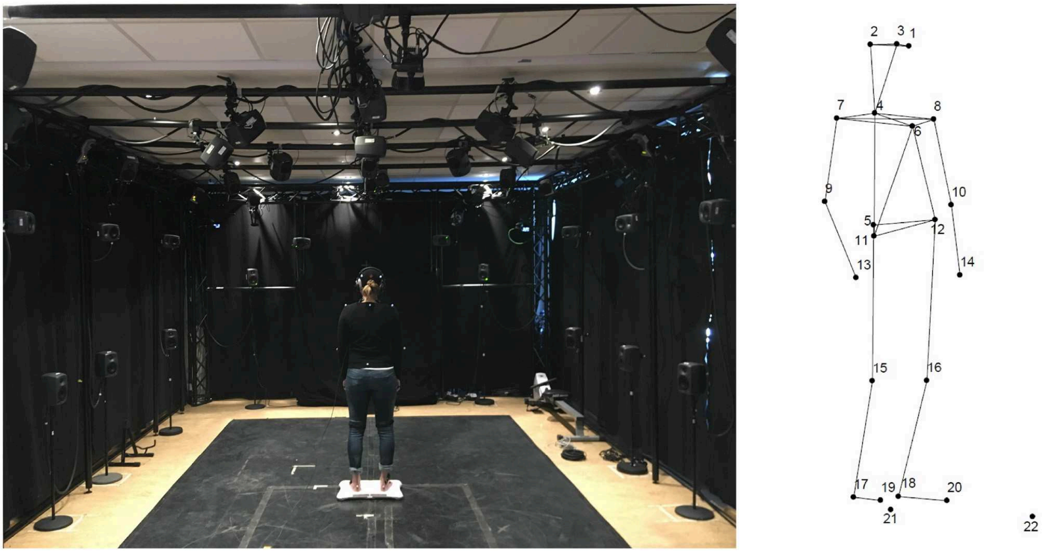

FIGURE 3 | (Left) Laboratory setup and one participant standing during the headphones condition. Written informed consent was obtained from the participant for publication of images. **(Right)** Motion capture reconstructed markers and segments. The markers were located as follows (L, left; R, right; F, front; B, back): 1—F head; 2—RB head; 3—LB head; 4—B neck; 5—sacrum; 6—sternum; 7—R shoulder; 8—L shoulder; 9—R elbow; 10—L elbow; 11—R hip; 12—L hip; 13—R wrist; 14—L wrist; 15—R knee; 16—L knee; 17—R heel; 18—L heel; 19—R toe; 20—L toe; 21—reference marker on the Wii board; 22—reference marker on the floor.

were randomly assigned to one of the groups (starting with headphones or starting with speakers). In the final sample, 11 females started with headphones and 7 with speakers, and 7 males started with headphones and 11 with speakers. Participants were asked to put on a motion capture suit, and EMG electrodes were placed on each foot, forearm and shoulder. In addition, a breathing sensor was placed on the torso. The EMG and respiration measurements were added for methodological experimentation, and will not be included in the current analysis. The same is the case for the data from the Wii balance platform that the participants were standing on (see **Figure 3** for illustration of the setup in the lab).

When ready, participants were asked to stand on the balance platform and remain in a relaxed, comfortable position during the experiment. They were asked to look in the direction of a white cross placed on a black wall in front of them (340 cm away from the platform). No specific instructions to move to the music or to try to stand still were provided (see **Appendix** for a script of the instruction). After the first recording session, the participants were asked to sit down and fill in the first set of questionnaires. When the participants were ready, the second listening session took place, followed by the filling in of the remaining set of questionnaires. The total duration of the experiment was around 1 h 15 min, with small variations depending on time spent on preparation and on filling in the questionnaires.

2.6. Analysis

Analysis of the motion capture data started with the extraction of the position of the Center of Mass (CoM) based on the position of the marker placed on the sacrum (lower back) as in Mapelli et al. (2014). Next, head position was calculated from the middle point between the markers placed on both sides of the parietal area of the head (see **Figure 3** for reference). The Whole Body Motion (Body) was measured by calculating the average position of all 20 markers for each sample. Head position data from two participants were incomplete, and therefore, were excluded, resulting in a sample of 33 participants for the head position data and a sample of 35 participants for CoM and Body data. The magnitudes of the CoM, Head, and Body velocity vectors were computed by differentiating the position data. The extraction of position data and computation of velocities were done in Matlab using the MoCap toolbox (Burger and Toiviainen, 2013). Mean CoM, Head, and Body velocity data for each participant and each session were then split into music and silence segments, and only the music segments were used for the statistical analysis. Although initially an analysis of silence segments, and a comparison of silence and music segments, were planned, they were not performed due to procedural problems that are described in the Discussion.

Analysis of the sound stimuli was performed using the MIRtoolbox (Lartillot et al., 2008). We decided to focus on

TABLE 3 | Mean, standard deviation, and median values for the answers to questions asked after each listening session: "Did you feel that you were moving?"; "Did you feel tired during standing?"; "Did you perceive the music as loud?" ($N = 35$).

	Moving			Loudness			Tiredness		
	Mean	**SD**	**Median**	**Mean**	**SD**	**Median**	**Mean**	**SD**	**Median**
Headphones	2.7	1.1	2.0	2.4	1.2	2.0	2.5	1.1	3.0
Speakers	2.7	1.1	3.0	2.3	1.1	2.0	2.2	1.1	2.0

The answers were provided on a 5-point scale ranging from "No" to "Very much" (no descriptions in between; coded as ranging from 1 to 5).

TABLE 4 | Questions about headphones and speakers—experiences during the experiment and habits of using both playback methods in everyday life ($N = 35$).

Question		Mean	SD	Median
1	Which part of the experiment felt more comfortable—headphones or speakers?	3.3	1.2	3.0
2	Did you feel that you moved more while using headphones or speakers?	3.0	1.1	3.0
3	Did you perceive music in headphones or in speakers as louder?	2.6	1.3	3.0
4	Do you enjoy listening to music at loud volume from headphones?	3.3	1.3	4.0
5	Do you enjoy listening to music at loud volume from speakers?	3.5	1.3	4.0
6	How often do you use headphones to listen to music?	58%	29%	60%
7	How often do you use speakers to listen to music?	42%	29%	40%

For questions 1–5, answers were provided on a 5-point scale: for questions 1–3, ranging from "Definitely headphones" to "Definitely speakers," and for questions 4 and 5, ranging from "Definitely not" to "Very much" (no descriptions in between; coded as ranging from 1 to 5). For questions 6 and 7, the answers were formulated as the "_% of the time".

rhythmic complexity, and this was measured based on the *event density* of the tracks. This feature was extracted with the `mireventdensity` function of the MIR Toolbox, and is based on counting the peaks of the envelope of the waveform. The event densities are summarized in **Table 2**. The median value of the six tracks was 229.5 events, and this value was used to separate the stimuli into two categories: low (Metronome, Rhythm, Bratten) and high (Neelix1, Neelix2, and Pysh) event density.

Analysis of the questionnaire and movement velocity data was performed using IBM SPSS Statistics 25. A repeated measures $2 \times 2 \times 3$ ANOVA was performed with playback method (headphones/speakers), event density (low/high), and movement measure (Head/CoM/Body) as within-subject factors, in order to assess the significance of each factor and potential interactions between factors. Due to the non-normal distribution of scores in some of the questionnaire items, Spearman's rank correlations were computed between questionnaire and movement data, as well as between relevant questionnaire items.

TABLE 5 | Values of the mean and standard deviation of the velocity (mm/s) for each of the motion measures (Head, Center of Mass, Body) during music listening in each condition.

	Head ($N = 33$)		CoM ($N = 35$)		Body ($N = 35$)	
	M	**SD**	**M**	**SD**	**M**	**SD**
Headphones	14.4	6.8	6.6	1.8	7.8	1.8
Speakers	11.7	3.2	6.2	1.6	7.3	1.3

The discrepancy in included participants is due to missing head markers data from two participants.

3. RESULTS

3.1. Motion Capture Data

The results of the $2 \times 2 \times 3$ repeated measures ANOVA showed a significant effect of the playback method [$F_{(1,32)} = 10.09$, $p = 0.003$] and a significant effect of the movement measure [$F_{(1,64)} = 74.48$, $p < 0.001$, with a Greenhouse-Geisser correction] on the observed movement velocity, as well as an interaction between the playback method and the movement measure [$F_{(1,64)} = 6.61$, $p = 0.013$, with a Greenhouse-Geisser correction]. No significant effect of the event density, and no interaction between the event density and playback method or between the event density and movement measure were observed.

To explore the interaction between the playback method and movement measure, we performed repeated measures ANOVAs for each movement measure. These showed that the playback method had a significant effect on Head [$F_{(1,32)} = 9.07$, $p = 0.005$] and Body [$F_{(1,34)} = 4.61$, $p = 0.039$], but it did not have a significant effect on CoM [$F_{(1,34)} = 2.43$, $p = 0.129$].

Means and standard deviations of the Head, CoM and Body velocities of all participants in both the headphones and speakers conditions are shown in **Table 5**. **Figure 4** shows the means and confidence intervals for all participants across the whole 8-min session.

No significant movement velocity differences were observed between male and female participants in any of the three movement measures, when compared using an independent samples t-test. However, a significant correlation was found between the participants' height and their Head data in both headphones ($rp = 0.393$, $p = 0.024$) and speakers ($rp = 0.440$, $p = 0.01$) conditions. This indicates that taller participants on average moved their head more during music listening. No significant correlations were found between the participants' height and their Body or CoM data in the two listening conditions.

3.2. Questionnaire Data

A Wilcoxon test was performed for the questions that were answered after each listening session. The analysis showed that participants reported feeling more tired during the headphones listening session (Mdn = 3) than during speakers listening session (Mdn = 2) ($Z = -2.049$, $p = 0.040$). No significant differences in perceived loudness or perceived amount of movement were observed (**Table 3**).

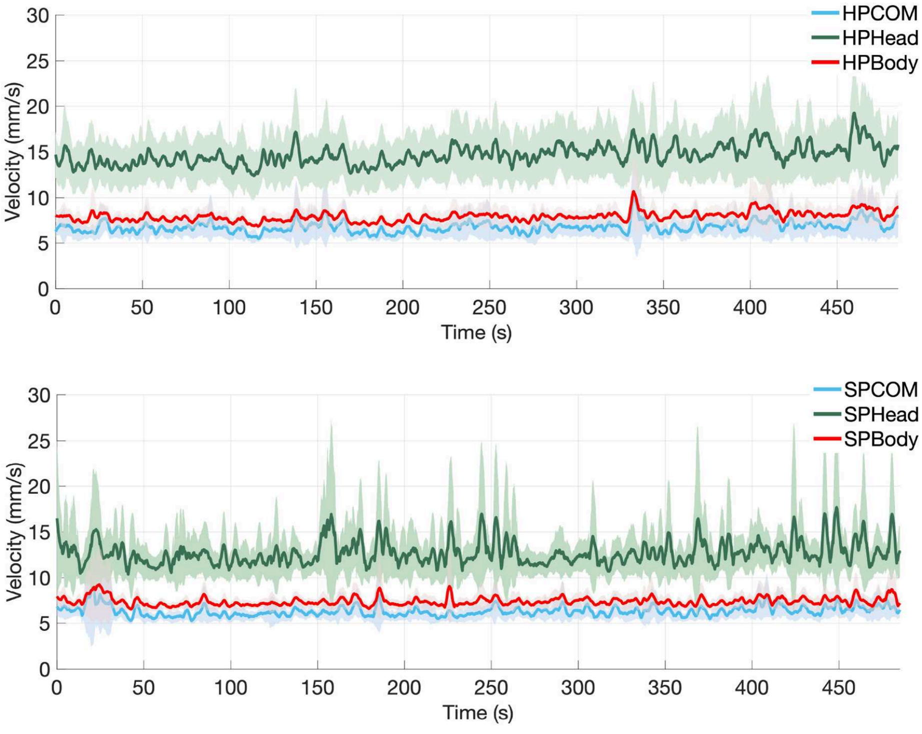

FIGURE 4 | Mean velocity values of Head Motion (Head), Center of Mass (CoM), and Whole Body Motion (Body) across all participants, with 95% confidence intervals for the headphones condition (top) and for the speakers condition (bottom) for the whole trial (a total of 480 s, consisting of alternating segments of 30 s of silence and 45 s of sound stimuli, starting and ending with silence).

Means and standard deviations of answers to further questions that related directly to using headphones and speakers, either in everyday life or during this experiment, are reported in **Table 4**. With regards to the question, “Which type of headphones do you usually use?” usage of in-ear headphones was reported 19 times, on-ear headphones 11 times, and around-ear headphones 12 times. A schematic picture of each type of headphones was included in the questionnaire, to ensure that the participants understood the question. Two participants reported not using headphones at all in their everyday life (6% of participants), 25 reported using one type (71% of participants), 7 using two types (20% of participants), and one using all three listed types of headphones (3% of participants).

A Spearman’s rank correlation revealed that enjoyment of listening to music played loud on headphones correlated with the regularity of headphones use ($rs = 0.364$, $p = 0.032$) and enjoyment of listening to music played loud on speakers ($rs = 0.563$, $p < 0.001$). A positive correlation was found between enjoyment of listening to music played loud on headphones and hours spent weekly listening to music ($rs = 0.339$, $p = 0.047$), and, at a trend level, between regularity of speakers use and age ($rs = 0.332$, $p = 0.052$).

Many significant correlations were found between habits of using headphones and speakers, and enjoyment of the music stimuli used in the experiment. Enjoyment of listening to music played loud on headphones correlated with liking both songs by Neelix ($rs = 0.641$, $p < 0.0001$ and $rs = 0.446$, $p < 0.0001$) and an average liking of all stimuli ($rs = 0.641$, $p = 0.007$). It also correlated with liking the song by Pysh, but only at the verge of significance ($rs = 0.332$, $p = 0.051$). Enjoyment of listening to music played loud on speakers correlated with liking the song by André Bratten ($rs = 0.471$, $p = 0.004$), both songs by Neelix ($rs = 0.348$, $p = 0.041$ and $rs = 0.361$, $p = 0.033$), as well as with an average liking of all stimulus $rs = 0.402$, $p = 0.017$). Regularity of headphones use negatively correlated with enjoyment of the metronome track ($rs = -0.358$, $p = 0.035$).

The questions about headphones and speakers correlated with music preference scores from the STOMP questionnaire. These exploratory analyses revealed several significant correlations, which are reported in **Table 6**.

TABLE 6 | Coefficients of Spearman's rank correlations between questions about headphones and speakers and STOMP items ($N = 35$).

Question	Classical	Dance/ Electronica	Religious	Pop	Heavy metal	Soundtracks/ Theme songs	Reflective/ Complex	Upbeat/ Conventional	Energetic/ Rhythmic
1	0.251	0.103	−0.044	0.178	0.040	0.028	−0.153	−0.089	−0.023
2	0.454**	−0.045	0.233	0.035	−0.037	0.375*	0.055	0.348*	−0.185
3	−0.269	0.083	0.045	−0.046	−0.335*	−0.134	−0.217	−0.076	0.077
4	−0.175	0.678**	−0.112	0.245	0.330	−0.026	−0.188	−0.083	0.485**
5	0.193	0.225	−0.370*	0.023	0.527**	−0.106	−0.024	−0.195	0.182
6	−0.271	0.509**	0.019	0.366*	−0.101	0.218	−0.392*	0.107	0.282
7	0.271	−0.509**	−0.019	−0.366*	0.101	−0.218	0.392*	−0.107	−0.282

*Significant values are marked in grey. **indicates significance at the 0.01 level and *at the 0.05 level. Questions numbers are explained in* ***Table 4****. No significant correlations were found for the following categories: Blues, Country, Folk, Rap/Hip-Hop, Soul/Funk, Alternative, Jazz, Rock, Intense/Rebellious.*

3.3. Correlations Between the Questionnaires and Motion Capture Data

Spearman's rank correlations were performed between questionnaire data and the velocity of Head, CoM and Body. Here it was found that Head in the headphones condition correlated significantly with age ($rs = -0.382$, $p = 0.028$) and liking to dance ($rs = 0.451$, $p = 0.008$). Body velocity in the headphones condition correlated significantly with liking to dance ($rs = 0.402$, $p = 0.017$). The self-reported subjective feeling of moving more while listening to headphones correlated with the velocities of CoM ($rs = 0.503$, $p = 0.002$) and Body ($rs = 0.392$, $p = 0.020$) in the headphones condition. No significant correlations were found between the velocity measures and the responses to the STOMP questionnaire.

4. DISCUSSION

We discuss below the results from the experiment with respect to the three research questions posed in the introduction: whether different playback methods influence the spontaneous movement (RQ1), and if so, whether these differences are related to the musical complexity of the stimuli (RQ2) and/or to the participants' individual differences (RQ3).

4.1. Movement Differences for Headphones and Speakers

The clearest finding from the present study is the significantly higher mean velocity of the Head and Body motion capture data during headphones listening as compared to speakers listening. There are several potential explanations for this finding. First, wearing headphones that cover the ears restricts the participants' capacity to hear ambient sounds of the environment. Previous studies have shown that wearing ear defenders increases postural sway in healthy subjects (Kanegaonkar et al., 2012). The similarity of ear defenders to the tightly fit around-ear headphones used in our study may lead us to extrapolate that this is a possible cause for the higher velocity of movement observed while listening to headphones. However, we have not found any studies that compare postural stability during headphones vs. speakers use, or between different headphone designs. If headphones (including different types of headphones) have a disruptive impact on balance, this playback method should perhaps be reconsidered in movement experiments, and especially in the field of posturography.

Another plausible explanation for why participants moved more while listening to music using headphones, is that they were able to better enjoy the music. Perhaps the proximate location of the sound from headphones results in stronger reactions to music due to the stimulation of the vestibular system, causing pleasurable sensations of self-motion (Todd and Cody, 2000; Todd et al., 2008). It could also be that the participants experienced the use of headphones as more natural or comfortable than listening to speakers. Similarly, if headphones do, indeed, increase the feeling of intimacy or safety, it is possible that they helped participants forget about the laboratory setting and the presence of the experimenter in the back of the room. There is, however, no direct evidence that people move more to music when they feel comfortable or safe, or when they listen attentively, but it seems likely that such factors are of importance.

Interestingly, the playback method did not have a significant effect on the CoM measurements. Moreover, Head data was notably higher than the data from both CoM and Body. These differences can be explained through the dynamics of balance and posture control, and the inverted pendulum model of human posture (Winter, 2009). In a stable, standing posture, CoM should always present a smaller range of motion when compared with distant body segments. Burger et al. (2013) showed how free movement to music differs significantly between body segments, and in particular between the head and the rest of the body. A clear pulse was shown to induce whole body movement, while percussiveness seemed to induce clearer patterns from the participants' heads and hands. Our data confirms that Head, CoM and Body should be treated as complementary measures that can to different degrees depict small spontaneous body movement during music listening. In the future, it would be worthwhile to explore which of these and similar measures (such as movement of particular limbs) are most effective for capturing body sway and posture adjustments, and which are best for analysing spontaneously occurring movements that synchronize to musical rhythms. Extracting various features of the stimuli, and correlating them with the qualitative and quantitative aspects of such movements, may help to understand which sound features are important for spontaneous movement responses to music.

Participants, on average, reported that listening to headphones during the experiment was more tiresome than listening to the speakers. This is an interesting finding, which to our knowledge has no precedent in comparative studies on headphones and speakers use. In a study by Nelson and Nilsson (1990), the participants who listened to music over headphones or speakers while driving in a car simulator did not report differences in fatigue. It should be noted, however, that in this study, music was used as a background for performing other tasks. The other comparative studies reported here did not include participant reports on general tiredness or listening fatigue. Also, to our knowledge, there have not been any studies on the relationship between headphones use and listeners' fatigue in different contexts. However, several authors claim that the pressure exerted by sound on the eardrums, together with the in-head localization of sound in headphones, commonly result in listening fatigue (Bauer, 1965; Iwanaga et al., 2002; Vickers, 2009).

4.2. Musical Complexity

The experiment was designed with using six stimuli with varying level of musical complexity. Our primary interest was on rhythmic complexity, although the tracks' complexity also varied in other musical dimensions. We decided to use event density as a measure of rhythmic complexity, and for grouping the stimuli into two categories (low and high complexity). This is, of course, a crude reduction of rhythmic complexity, but it still manages to capture some of the core differences between the tracks in an efficient manner.

We did not find a significant effect of the rhythmic complexity on the movement responses. While this may seem surprising, it is in line with the results from a different study using the same stimuli (González Sánchez et al., 2019). One explanation for the lack of significance here may be that it is primarily the presence of a steady beat that drives the spontaneous movement responses. This fits with findings from some of our previous studies, in which EDM has led to more movement than other types of music with less clearly defined beat patterns (Jensenius et al., 2017; González Sánchez et al., 2018). It could have been interesting to perform correlation analysis per track, and also to carry out a more detailed musical analysis of the tracks in question, but that was out of the scope for this article.

4.3. Individual Differences

As we discussed in the introduction, there are differences in how people like to use headphones and speakers. These differences can be partially explained by factors such as age and music preferences. We found that older participants use speakers more often than headphones. This is in line with the results of a survey reported by Fung et al. (2013), which showed that younger adults (age 18–44 years) listen to music on headphones more than older adults. Interestingly, Kallinen and Ravaja (2007) report that 60% of the participants expressed a preference for listening to the news on headphones, as opposed to 40% who preferred to use speakers. In our study, the average self-reported usage of both playback methods in everyday life turned out to be 58% for headphones and 42% for speakers. These results seem similar, but it is also important to consider that preferences and actual use are not equivalent. There are many possible reasons for why people would buy and use headphones or speakers in everyday life, even though they might prefer to use a different playback system (see section 1.1.1). Our data also shows that enjoying listening to loud music over headphones correlates with the regularity of using headphones, but no such analogous relationship was observed for speakers. This can be a relevant finding for studies that deal with listener preferences and styles of engaging with music, as they may be dependent on the playback method used in a given context.

Another interesting finding was that people who like dance music also like to listen to music at a loud sound level over headphones, and that they report to use headphones more often than speakers. While one might expect to encounter dance music played over speakers at parties, considering the current popularity of EDM (Watson, 2018), it is not surprising that people listen to it over headphones also during everyday activities. Listeners may turn up the sound level to boost the energizing effect of the music and increase the feeling of pleasure (Todd and Cody, 2000). However, a more thorough study on the personal use of music is needed to confirm such speculations. This could also shed light on whether people consciously use a specific playback method in order to obtain a specific feeling (or perhaps when listening to different genres), and not only for pragmatic purposes. When it comes to preference for music genres, our data show some interesting correlation patterns with playback method. For example, we find that a preference for heavy metal music correlates with liking of listening to music played loudly on speakers, but not on headphones. This finding could aid the design of a study that focuses on this genre or includes such music material.

4.4. Limitations

There are several limitations in the design of this study. One is possible familiarity effects, since all participants had to listen to each stimulus twice (using both headphones and speakers). People generally tend to like songs that they have heard before more than when they listen to them for the first time (Peretz et al., 1998), even though after a certain number of repetitions, the positive affect becomes diminished (Hargreaves, 1984). Such changes in affect could be reflected in bodily responses to music; the data from the second session may be different from the first one simply based on the fact that the participants were already familiar with the stimuli. However, since the presentation order was counterbalanced between participants, we believe that it should not be considered as a bias factor for this study.

Another limitation of this study is that only one type of headphones and speakers were used. The choice of around-ears headphones and a stereo speaker setup was motivated by the common occurrence of these two scenarios in research on music-related body movement. As mentioned earlier, there are many different types and brands of headphones and numerous speaker configuration possibilities. It would be interesting to conduct more studies that investigate in more detail the effects of both different types and designs of the playback devices.

The decision to only include EDM-like music stimuli in this article may also be considered a limitation. Even though we found that EDM music has a particularly strong effect on body movement in our previous studies (Jensenius et al., 2017; González Sánchez et al., 2018), using other types of music (e.g., classical) may have produced different results. Therefore, the findings of this study should not be generalized to all genres of music. It could also be mentioned as a limitation that we were using real music with a lot of different musical variables. This was the reason we decided to include the two "synthetic" control tracks (Metronome and Rhythm) alongside the real music examples. In the future it would be interesting to try to get access to a real-world multi-track recording. Then it would be possible to experiment with the different musical layers in a more systematic manner.

We made sure that the participants included in this study had not previously participated in any of our standstill studies, which have publicly been known as "Championship of Standstill" (Jensenius et al., 2017; González Sánchez et al., 2018; González Sánchez et al., 2019). This was because the experimental design here was slightly different than in the previous studies. In the present study, participants were not instructed to stand as still as possible; they were asked to stand on the platform in a relaxed, comfortable position, with their arms at the sides of their body, and to remain in this neutral position during the experiment (see **Appendix** for a script of the instructions). They were also instructed to look toward a white cross on the wall. However, these instructions, combined with prior knowledge of our previous studies, might have encouraged some participants to try to not move at all. At the same time, many participants felt free to move subtly to the rhythm of the music. Thus, participants may have interpreted the study instructions differently, leading to an increased between–participant variance in the motion capture data. Moreover, some participants seemed to treat the silence between the tracks as a break, using this time to discretely stretch, straighten their posture, etc. They might have thought that it was only their body movement in response to the music that would be analyzed. We were originally also interested in the movement during silence segments, but had to abandon this comparison due to these inconsistencies in the data. Fortunately, no instances of touching the headphones or adjusting the motion capture suit were observed, neither during the music nor the silence segments. In future studies, more care should be taken when it comes to formulating the instructions in such a way as to avoid implicit directions to try not to move, and to ensure that the participants understand that the whole recording session, including silences, is to be analyzed.

Due to the nature of this study, it is not possible to conclude that the observed movement was fully dependent on the sound stimuli. However, by using three different motion capture measures, we aimed to reduce the probability of biases stemming from fidgeting and posture adjustments. For example, the CoM measure is less sensitive to arm movement. In the future, different types of movement analyses (for example, employing measures of entrainment to rhythm) might reveal further data about spontaneous body movement in both listening scenarios.

Individual differences, such as listening habits, music preferences, and body morphology, emerged as interesting factors in relation to spontaneous body movement in response to music listened over headphones and speakers. As indicated in the results of Kallinen and Ravaja (2007), some personal traits may influence body movements in response to music listened to through both playback methods. We believe that a more detailed analysis of individual differences could show interesting patterns in subtle, spontaneous body movement to music, also independently of the playback method.

5. CONCLUSIONS

Although there are still many open questions, this exploratory study has demonstrated that using headphones and speakers as playback methods can result in different patterns of body movement in a music listening experiment. Coming back to the original research questions, we can conclude that:

1. The participants moved on average more when listening to music with headphones than with speakers. This difference was particularly significant for head movement.
2. Complexity of the stimuli did not have a significant effect on the observed movement in headphones or speakers listening.
3. Individual differences correlate with body movement in response to music, and the pattern of these correlations is different for headphones and speakers listening.

Considering the potential effects of wearing headphones on postural control and the vestibular system, as well as the other features of both playback methods discussed in this article, careful choosing between them seems to be especially important for research paradigms in which the main interest is in body movement to music. Future studies are needed to better understand the impact of these two playback methods on bodily responses to music, and to explore potential differences between different types of headphones and speaker setups. Moreover, the patterns of preferences for music listening between headphones and speakers were shown to be asymmetrical, and the relationships between these preferences, listening habits, and individual traits should be further explored.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The study was reviewed and approved by Norwegian Center for Research Data (NSD), under the project identification number 58546. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

AZ, VG-S, AJ, and BL contributed to conception and design of the study. AZ and VG-S performed the experiments and statistical analysis. VG-S pre-processed the data. AZ wrote the first draft of the manuscript. AZ, VG-S, and AJ wrote the sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

The script used for the oral instruction given to participants at the beginning of the experiment:

> Please stand on the force platform in a relaxed, comfortable position with your arms at the sides of your body. Try to remain in this neutral position during the experiment. Keep your eyes on the white cross on the wall. You will hear some rhythms and music, with periods of silence between them, and the experiment will last about 8 min. We will start with 30 seconds of silence. Is the instruction clear?

Paper IV

Who moves to music? Empathic Concern predicts spontaneous movement responses to rhythm and music

Agata Zelechowska, Victor E. Gonzalez-Sanchez, Bruno Laeng, Jonna K. Vuoskoski, Alexander Refsum Jensenius

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Who moves to music? Empathic Concern predicts spontaneous movement responses to rhythm and music

Agata Zelechowska[1,2], Victor E. Gonzalez-Sanchez[1,2], Bruno Laeng[1,3], Jonna Vuoskoski[1,2,3] and Alexander Refsum Jensenius[1,2]

Abstract
Moving to music is a universal human phenomenon, and previous studies have shown that people move to music even when they try to stand still. But are there individual differences when it comes to how much people spontaneously respond to music with body movement? This article reports on a motion capture study in which 34 participants were asked to stand in a neutral position while listening to short excerpts of rhythmic stimuli and electronic dance music (EDM). We explore whether personality and empathy measures, as well as different aspects of music-related behaviour and preferences, can predict the amount of spontaneous movement of the participants. Individual differences were measured using a set of questionnaires: Big Five Inventory (BFI), Interpersonal Reactivity Index (IRI), and Barcelona Music Reward Questionnaire (BMRQ). Liking ratings for the stimuli were also collected. The regression analyses show that Empathic Concern is a significant predictor of the observed spontaneous movement. We also found a relationship between empathy and the participants' self-reported tendency to move to music.

Keywords
music-induced movement, spontaneous movement, motion capture, EDM, rhythm, individual differences, empathy

Moving to music is a phenomenon observed in all known human cultures (Sievers et al., 2013), and spontaneous music-related movement appears as early as in infancy (Zentner & Eerola, 2010). Spontaneous movement to music can come in many forms, such as, feeling the urge to dance, tapping a foot, or adjusting the tempo of walking. We have been particularly interested in spontaneous movement happening when people try to stand still (Jensenius et al., 2017; González Sánchez et al., 2018). The measured motion of the head during still standing is typically less than 10 millimetres per second, what we refer to as *micromotion*. This level of micromotion appears to be fairly similar across people of different ages, heights, genders, and musical backgrounds. But we have been curious to understand more about whether there are individual differences between people that can explain the extent to which they will spontaneously respond to music with body movement? This question is based on studies suggesting that peoples' individual traits are associated with the quantitative and qualitative properties of their movement to music (Luck et al., 2009, 2010; Carlson et al., 2016; Bamford & Davidson, 2017). In this article, our aim is to answer the question: which individual characteristics make people more likely to move to music?

Spontaneous movement responses to music

Bodily responses to music can be divided into two main categories: *physiological* and *physical* (Hodges, 2009). Physiological responses manifest through various bodily phenomena, such as, changes in skin conductivity, muscular tension, heart rate, respiration, body temperature, pupil diameter, and so on. Physical responses, on the other hand, are related to movement of the body. Several studies have dealt with body movement as a specific activity connected to experiencing music (Gritten & King, 2006, 2011; Godoy & Leman, 2010). There are fewer studies that have investigated spontaneous—that is, unplanned, resulting from an impulse—motor responses to music. It is common to say that music 'moves us,' which suggests that movement to music is an outcome of an external 'force,' as opposed to a conscious decision to move. The underlying mechanisms that cause such an urge to move, however, are not yet fully understood.

It has been shown that music, as well as simple auditory rhythms, influence human posture by altering body sway and encouraging spontaneous motor synchronisation to the rhythmical structure (Ross et al., 2016; Coste et al., 2018). In our own studies on involuntary body movement, we have shown that music with a clear rhythmic structure significantly increases the amount of head movement (Jensenius et al., 2017; González Sánchez et al., 2018).

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[1] RITMO Centre for Interdisciplinary Studies in Rhythm, Time and Motion, University of Oslo, Norway
[2] Department of Musicology, University of Oslo, Norway
[3] Department of Psychology, University of Oslo, Norway

Corresponding author:
Agata Zelechowska, RITMO Centre for Interdisciplinary Studies in Rhythm, Time and Motion, Postboks 1133, Blindern, 0318 Oslo, Norway
Email: agata.zelechowska@imv.uio.no

This was found in motion capture studies in which people were asked to stand as still as possible while listening to alternating music excerpts and silence. Other researchers have shown that subtle body movement, such as head nodding, can appear spontaneously while engaging in different music-related tasks even when participants are not given any instructions regarding movement (Kilchenmann & Senn, 2015), or where the focus is on a different body part (Hurley et al., 2014). Other studies have highlighted the role of body movement in interpreting rhythmic structures (Su & Pöppel, 2012; Phillips-Silver & Trainor, 2008, 2007, 2005). Thus, there is ample evidence that body movement is crucial for the processing of rhythm and music.

The concept of 'groove' in music is often explained in relation to body movement, rhythm and pleasure (Câmara & Danielsen, 2018). Studies on groove typically focus on musical features, such as the level of syncopation (Witek et al., 2014, 2017) or microtiming (Davies et al., 2013; Skaansar et al., 2019), that make music feel 'danceable' and inspiring to move. However, groove can be also viewed as a psychological construct of a subjective sensorimotor response to music (Skaansar et al., 2019). Such response can be in the form of *wanting* to move (Janata et al., 2012; Madison, 2006), feeling an *impulse* to move (Senn et al., 2019), getting an *urge* to move (Senn et al., 2018), or that music *makes* one move (Madison, 2006). Some researchers specifically use the term 'groove response' to refer to such experiences (Janata et al., 2012; Senn et al., 2019, 2018). Experimental research on groove is largely based on paradigms that measure people's self-reported desire to move, and not the actual body movement, although there are some recent exceptions (Witek et al., 2017). Although the main focus is still on the properties of music, there are now indications that individual differences may be equally, or perhaps even more, important in explaining groove responses to music (Senn et al., 2018, 2019). We will describe some of these and other relevant findings in the following section.

Individual differences in bodily responses and movement to music

Previous studies have identified a number of participant characteristics that are relevant for various types of bodily responses to music (Gingras et al., 2015; McCrae, 2007; Nusbaum & Silvia, 2011; Laeng et al., 2016), as well as for different features of spontaneous dance (Burger et al., 2013; Luck et al., 2010, 2014). In the present study, we focus on a selection of previously reported personality variables, hypothesising that they might be related not only to various aspects of movement to music, but also to the tendency to engage in such movement spontaneously.

Personality

In the psychology literature, personality traits are typically classified according to a five-factor model that includes Openness to Experience, Conscientiousness, Extraversion, Agreeableness and Neuroticism (John et al., 2008). To our knowledge, only a few studies have examined the relationship between such personality traits and physiological responses to music. These studies have shown that people with high Openness to Experience are more prone to aesthetic chills (McCrae, 2007; Nusbaum & Silvia, 2011). In terms of body movement, Luck et al. (2009, 2010, 2014) analysed motion capture recordings of free dance to music and found that different movement patterns can be associated with different personality traits. They found that Openness and Agreeableness were associated with smooth movement, and that Extraversion and Conscientiousness correlated with higher movement speed (Luck et al., 2009), although for Conscientiousness the results only approached significance. In a later study, Luck et al. (2010) observed particularly strong connections between Extraversion and Neuroticism and specific movement patterns. They found that Extraversion was linked to fast movement of the head, hands, and centre of mass; and also an overall higher amount and energy of global and local body movement. In one of the studies, Neuroticism was associated with lower levels of global and local movement (Luck et al., 2009), while both of the previously mentioned studies found that Neuroticism was related to jerky and accelerated movement (Luck et al., 2009, 2010). More recently, Carlson et al. (2016) showed that low Conscientiousness and high Extraversion are associated with responsiveness to small tempo changes in dance.

Empathy

Empathy can be defined as an individual's 'responsivity to the other' (Davis, 1983). While it is typically associated with sharing emotions of the other person, it also can modify interactions between people at a physical level. It has been previously shown that empathy increases the so called ”chameleon effect”, referring to people nonconsciously mimicking motor behaviours of their interaction partners (Chartrand & Bargh, 1999). This responsivity to another person's bodily actions may be connected to the Mirror Neuron System (MNS) in the motor cortex, which is activated both when we observe (see or hear) an action and when we execute it (Gallese & Goldman, 1998; Keysers et al., 2003; Kohler et al., 2002). In music perception studies, it has been shown that simply listening to rhythmic sounds activates regions of the brain responsible for planning and execution of movement (Grahn & Brett, 2007). Based on findings about MNS and motor areas of the brain involved in processing music, Overy & Molnar-Szakacs (2009) developed the model of Shared Affective Motion Experience (SAME), which emphasises the role of simulated motor actions in the perception and cognition of musical sounds. It is similar to the motor-mimetic hypothesis by Godøy (2003), who argues that (musical) sounds are experienced through motor resonance. Launay (2015) has developed this further into a model explaining how we sense agency in music through such motor-mimetic principles, and that this, in turn, results in a social experience.

Following such ideas about relationships between music and movement, Bamford & Davidson (2017) explored the relationship between empathy and certain aspects of movement to music. They found that participants who scored high in empathy adapted their movement faster to tempo changes in the presented music stimuli. The high-empathy participants also reported that they enjoyed dancing more often than participants with low empathy scores. Recently, Novembre et al. (2019) examined the effect of a particular component of empathy—empathic perspective-taking—on interpersonal coordination in a music-making task that required synchronising streams of sounds. They found that participants who scored high in this dimension were better at predicting the actions of their leading partner. They also found that pairs of people with high empathic perspective-taking scores were more accurate at synchronising their actions. These findings contradict the results of Carlson et al. (2016), who found no correlation between empathic perspective taking and responsiveness to tempo in dance; however, the two studies employed different experimental paradigms. In later research, Carlson et al. (2018) measured overall trait empathy instead of empathic perspective taking, and found a positive relationship between empathy and responsiveness to the movement of the partner in dance. Thus, while there is some evidence supporting a potential relationship between empathy and the urge to move to music, more research needs to be done to draw definite conclusions.

Music preferences

Some musical features appear to be similarly appreciated between people. For example, the preferred tempo for dance is typically in the range of 120–130 BPM (Moelants, 2003). Other aspects of music, such as genre, instrumentation, or the content of low frequencies, can be a matter of personal taste. It has recently been found that both preference for, and familiarity with, the music stimuli positively affects participants' experience of groove (Senn et al., 2018, 2019). In fact, these extra-musical parameters predicted the groove experience better than any of the music-related features. In terms of actual body movement, Luck et al. (2014) found that a preference for the music stimuli had an U-shape relationship with the amount of observed movement. Similarly, Gingras et al. (2015) and Laeng et al. (2016) found that participants' liking for the music excerpts modulated pupillary responses to these excerpts. Another study of spontaneous physiological responses to music showed that listening to preferred music can reduce anxiety levels by lowering the mean arterial blood pressure and heart rate (Walworth, 2003).

Music-related behaviour

Musical expertise is a variable that is often investigated in studies on groove and bodily responses to music. It has been shown that professional musicians associate groove with different genres than amateur musicians and non-musicians (Senn et al., 2018). Professional musicians are also more sensitive to musical features associated with groove, such as syncopation (Senn et al., 2019; Witek et al., 2017) and microtiming (Kilchenmann & Senn, 2015). Furthermore, it has been found that musical training modulates the effect of groove-evoking music on the motor system (Stupacher et al., 2013), as well as the individual's ability to synchronise to groovy music (Hurley et al., 2014; Skaansar et al., 2019). It is, however, worth considering how responsive people are to music regardless of musical training, and to find out which aspects of their musical experience they find rewarding and pleasurable.

The Barcelona Music Reward Questionnaire (BMRQ) is a self-report measure specifically developed for addressing different music-related reward experiences (Mas-Herrero et al., 2013). The questionnaire decomposes musical reward into five factors: Musical Seeking, Emotion Evocation, Mood Regulation, Social Reward, and Sensory-Motor. The final variable is particularly relevant for our present research, since it comprises questions that directly address the general feeling of wanting to move to music. The authors of the questionnaire observed that Sensory-Motor scores correlate positively with the personality trait Openness to Experience. However, since their analyses did not include other personality dimensions, there is no information on possible correlations with Conscientiousness, Extraversion, Agreeableness or Neuroticism.

Research questions and hypotheses

The data set used in this article is the same as used in a previous article (Zelechowska et al., 2020). That article focused on observable differences in body movement between two different listening scenarios: presenting the sound stimuli using either headphones or speakers. There, we found that there are, indeed, differences, and that listening to music on headphones leads to significantly higher quantity of motion on average. A secondary result was that there are different experiences, preferences and habits associated with the use of these two playback methods, largely varying between the participants. Here, the main goal is to explore the individual characteristics of the participants, and see whether these characteristics can explain the amount of spontaneous movement to music.

As seen above, the previous literature on relationships between individual traits (such as, empathy or personality) and movement to music, is both scattered and scarce. Yet, there appears to be some evidence pointing towards a connection between such traits and movement to music. We hypothesise that the amount of spontaneous body movement to music can be explained by some of the following variable groups: personality traits (McCrae, 2007; Nusbaum & Silvia, 2011; Luck et al., 2009, 2010), empathy scores (Bamford & Davidson, 2017), types of rewards drawn from music (Mas-Herrero et al., 2013), and preference for the experimental stimuli (Gingras et al., 2015). Given the many open questions, this study is necessarily exploratory in nature. The literature summarised above employed research paradigms and research questions significantly different to ours, typically investigating dynamic body movement or other types of bodily behaviour. Thus, we do not set up a directional hypothesis for each variable.

Methods

Participants

The participants for this study were recruited from the community around the University of Oslo. Exclusion criteria included hearing loss, neurological disorders, arthritis, orthopaedic conditions, recent injuries or balance disorders. We also avoided participants in the Norwegian Championship of Standstill, which is a separate experiment paradigm that we have been running for some years (Jensenius et al., 2017; González Sánchez et al., 2018, 2019). A total of 42 participants were recruited to the study. Due to incomplete data collection, one case of misunderstood instructions, and one late report of a foot injury, 5 participants were excluded from further analysis. Three more participants were identified as outliers after initial computation of quantity of motion for all participants. Out of those three, one participant started dancing, one was fidgeting and stretching throughout the recordings, and one was continuously twitching their head. The final dataset included in the analyses therefore consisted of 34 participants (18 female, 16 male; mean age = 27 years, SD = 5.5 years). Of the total sample, 23 participants reported having some musical training, either professional or self-taught, out of which 18 still practised playing an instrument or singing. Participation in the study was rewarded with a 200 NOK (approx. 20 EUR) universal gift card. The study obtained ethical approval from the Norwegian Center for Research Data (NSD), with the project identification number 58546.

Music stimuli

The music stimuli used in the experiment consisted of six excerpts: four EDM excerpts, one custom-made synthetic drum track, and one 'beat' track comprising a 120 BPM isochronous beat based on a synthetic bass drum sound. In our previous study on the same dataset, we were interested in comparing the six tracks for two different playback methods (Zelechowska et al., 2020). In this study, however, we are primarily interested in the responses to the four EDM excerpts. We have therefore chosen to exclude the synthetic drum track, and will only use the beat track as a reference track.

All the sound stimuli were approximately 45 seconds in duration (with small fade-ins and fade-outs for the EDM excerpts), were in quadruple meter, contained no lyrics, and had a tempo in the range of 120 to 138 BPM (see Table 4 for an overview, and Zelechowska et al. (2020) for more details). Waveform displays of the tracks can be seen in Figure 1. The displays are based on visualising the harmonic and rhythmic content in two different colours, using the sound separation algorithm of Fitzgerald (2010) and Driedger (2014) implemented in librosa for Python (McFee et al., 2015).

Each experiment consisted of two listening sessions. During each listening session (approx. eight minutes), all stimuli were played in random order, alternating with 30-second segments of silence. Each session also started and ended with silence. The loudness across excerpts was normalised by ear by three of the authors during the pilot phase. This was to ensure that the tracks were perceptually similar. Since the question of playback method (headphones versus speakers) is not relevant for the analysis performed in this article, we have averaged the movement observed in the two listening sessions.

Table 1. An overview of the music stimuli used in the study.

Artist	Song title / Label / Year	Seconds	Tempo (BPM)
Beat track	Custom-made	45 s	120
André Bratten	Trommer Og Bass / Correspondant / 2014	0:00 – 0:45	120
Pysh feat. Poludnice	Sadom (Original Mix) / Mono.Noise / 2017	0:28 – 1:13	123
Neelix	Cherokee (Extended Mix) / Kontor Records / 2017	1:07 - 1:52	138
Neelix	Cherokee (Extended Mix) / Kontor Records / 2017	4:32 - 5:17	138

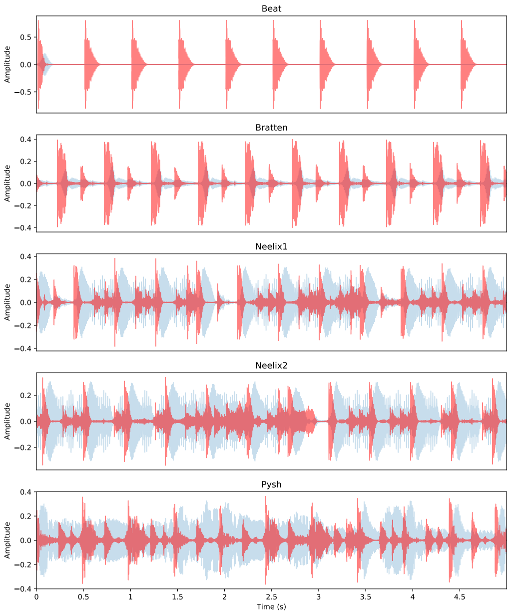

Figure 1. Waveform displays of 5 seconds of each of the five sound stimuli used in the analysis: the reference beat track (top) followed by the four EDM tracks: Bratten, Neelix1, Neelix2, and Pysh. The waveform has been split into two components: harmonic (grey) and rhythmic (pink), based on the method proposed by McFee et al. (2015).

Apparatus

A 12-camera infrared motion capture system from Qualisys (Oqus 300/500 cameras) was used to acquire the position data of 20 reflective markers attached to relevant anatomical landmarks on the subjects (Figure 2). The system was running at a 200 Hz sampling rate. A custom-made patch running in Max (Cycling '74) was used to play back the music stimuli in a randomised order. Uncompressed audio files were used for the experiment (.WAV files), played over an RME MADI-face Pro sound card. Synchronisation between the played audio files and the recorded motion capture data was achieved by sending a trigger signal from the motion capture system to the patch running the sound playback.

All subjects completed two listening sessions during the experiment, one with headphones and one with speakers. The headphones sessions were carried out with the sound stimuli presented through a pair of Beyerdynamic DT 770 PRO 80 Ohm headphones. The headphones were carefully placed on the participant's head, and the headband was adjusted as necessary. The speaker sessions were performed with a pair of Genelec 8020 loudspeakers and a Genelec 7050 sub-woofer. Each speaker was mounted on a stand at the height of 165 cm. The distance between the participant and each speaker was 315 cm, and the distance between the speakers was 290 cm. The sub-woofer was placed on the floor equidistant between the speakers, 245 cm away from the participant. The sound levels of both playback systems were high, but not uncomfortable. This meant a level of around 72 dB for speakers, and around 74 dB for headphones. The difference of 2 dB compensated for the lack of crosstalk when listening on headphones (McMullin, 2017). A short sound check was performed prior to the headphones session, to determine that the headphones volume was, indeed, loud but not uncomfortable. A total of eight subjects asked for lowering the volume (to either 72 dB or 68 dB).

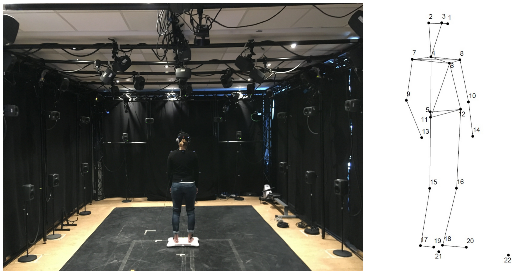

Figure 2. Left: Laboratory setup and one participant standing during the headphones condition. Written informed consent was obtained from the participant for publication of images. **Right**: Motion capture reconstructed markers and segments. The markers were located as follows (L, left; R, right; F, front; B, back): 1 - F head; 2 - RB head; 3 - LB head; 4 - B neck; 5 - sacrum; 6 - sternum; 7 - R shoulder; 8 - L shoulder; 9 - R elbow; 10 - L elbow; 11 - R hip; 12 - L hip; 13 - R wrist; 14 - L wrist; 15 - R knee; 16 - L knee; 17 - R heel; 18 - L heel; 19 - R toe; 20 - L toe, 21 - reference marker on the Wii board, 22 - reference marker on the floor.

Movement measures

The subjects wore a motion capture suit with 20 reflective markers placed on selected anatomical landmarks (Figure 2). The whole body movement was measured by calculating the average position of all 20 markers for each sample and differentiating the position data to obtain the norm of the velocity vector. Post-processing of the motion capture data was performed in Qualisys Track Manager (QTM) and the further analysis was performed in Matlab using the MoCap Toolbox (Burger & Toiviainen, 2013). The data from each listening session was then split into two segments: (1) EDM (the average of the four EDM tracks) and (2) beat track. The average movement velocity was computed for both of these segments. The data from the two types of listening sessions (headphones and speakers) were averaged to simplify the analysis.

Self-report measures

The participants were asked to fill in a set of questionnaires during the break between listening sessions and at the end of the experiment. The following sections describe the different questionnaires used.

Personality The Big Five Inventory (BFI; (John et al., 2008)) was used to evaluate the personality dimensions of the participants: *Extraversion, Agreeableness, Openness, Conscientiousness,* and *Neuroticism*. The questionnaire comprises 44 statements (e.g., *'I see myself as someone who worries a lot'*), each attributed to one of the five dimensions, and the answers are given on a five-point scale ranging from *'Disagree strongly'* to *'Agree strongly'*.

Empathy The Interpersonal Reactivity Index (IRI; (Davis, 1983)) was employed to assess participants' trait empathy. The IRI measures both the cognitive and affective aspects of empathy, divided into four subscales: *Fantasy, Perspective Taking, Empathic Concern,* and *Personal Distress*. It comprises 28 items (e.g., *'I really get involved with the feelings of the characters in a novel'*), which are rated on a five-point scale ranging from *'Does not describe me well'* to *'Describes me very well'*.

Music reward experiences The Barcelona Music Reward Questionnaire (BMRQ; (Mas-Herrero et al., 2013)) was employed to determine which aspects of a music experience are most motivating for participants. The questionnaire comprises 20 items (e.g., *'When I hear a tune I like a lot I can't help tapping or moving to its beat'*), which are grouped into five dimensions: *Emotional Evocation*, *Sensory-Motor*, *Mood Regulation*, *Musical Seeking*, and *Social Reward*. The ratings are given on a five-point scale ranging from *'Completely disagree'* to *'Completely agree'*.

Stimulus ratings At the end of the experiment, short excerpts of each of the stimuli were replayed so that the subjects could evaluate their liking of each track on a seven-point scale ranging from *'Dislike strongly'* to *'Like strongly'*. None of the Participants knew any of the songs used in the experiment, but some of them expressed general familiarity with the music genre.

Background variables A custom-made questionnaire was distributed at the end of the experiment, which included questions on age and gender, as well as on the number of hours spent weekly on: listening to music, playing/producing/composing music, dancing, and doing physical exercise (other than dance). We also asked about liking to dance (from *'Definitely not'* to *'Definitely yes'*). At the end, there were some questions on musical training based on items from the Beat Alignment Test (BAT; (Iversen & Patel, 2008)). An overview of the distribution of scores can be found in Table 2 and Table 3.

Procedure

The experiment took place in the fourMs Lab at the University of Oslo. The participants were invited to the laboratory individually and written informed consent was obtained prior to the experiment. During the preparation phase, the participants put on the motion capture suit and reflective markers were placed on selected points of their body (Figure 2). Additional data collection included EMG electrodes placed on each foot, forearm and shoulder, a breathing chest sensor, and a balance platform. These extra sensors were added as part of ongoing methodological experimentation in the lab, and were not part of the original study design. Data from these sensors will therefore not be analysed in the current article.

The subjects were instructed to stand on the balance platform in a relaxed, comfortable position. They were asked to focus their gaze on a white cross placed on the wall in front of them (340 cm away from the platform). No specific instructions about moving to the music or trying to stand still were provided. The complete oral instruction can be found in the Appendix.

After completing the first recording session, the participants filled in the first part of the questionnaires: their subjective experience of the session, as well as the BFI and IRI questionnaires. Then, after completing the second listening session, they filled in the remaining set of questionnaires: experiences from the second session, BMRQ, and also some other questionnaires that are not covered in the present analysis. Figure 3 shows a summary of the different steps of the study. The experiment took about 1 hour and 15 minutes to complete.

Analysis

Pre-processing of motion capture data was performed in Qualisys Track Manager, and the data were exported to Matlab for further processing using the MoCap Toolbox (Burger & Toiviainen, 2013). The average *quantity of motion* (QoM) was calculated as the first derivative (the velocity) of the whole body position data. The norm of the velocity was then calculated from the three components of the velocity vector. The resulting value was averaged across samples in each stimuli. The end result is one average QoM value per person per stimuli. The analyses of the questionnaires, and their correlations with the QoM data, were performed using IBM SPSS Statistics 25.

In order to explore whether any of the individual difference variables significantly predict the amount of movement in response to the two types of stimuli (EDM and beat), two regression analyses were run. The regression approach was a combination of the sequential and stepwise methods, where predictors are first tested in theoretically informed blocks using the stepwise method, and then significant predictors are entered into a final model in a predetermined order (Tabachnick et al., 2007). This approach mitigates some of the weaknesses of the simple stepwise method (namely the limitation that the fit of variables is assessed based on other variables in the model) by enabling more predictors to be entered into the final model. The predictor variables were grouped into hierarchical blocks in terms of their level of specificity, starting with broad, stable personality traits (Block 1), followed by trait empathy (Block 2), kinds of musical reward (Block 3), and liking for the experimental stimuli (Block 4). Within each block, we tested for significant predictors using the stepwise method in SPSS. In essence, this method uses forward selection, but additionally each time a predictor is added to the model, a removal test is applied to the least useful predictor in the model. Probability of F was used as the stepping criterion, with $p < .05$ as the threshold of entry into the model, and $p > .10$ as the threshold for removal. Separate regression analyses were carried out for QoM in response to EDM and the plain beat stimulus. EDM carries with it a multitude of associations (to dancing, clubbing, etc.), so the simple beat track functioned as a more neutral control stimulus to test whether similar—or different—predictors explain the QoM in the two cases.

The dependent variable was the QoM in response to each stimulus type. The independent variables that were tested blockwise comprised:

- Block 1: Five subscales of BFI: *Openness to Experience, Conscientiousness, Extraversion, Agreeableness, Neuroticism*
- Block 2: Four subscales of IRI: *Fantasy, Perspective Taking, Empathic Concern, Personal Distress*
- Block 3: Five subscales of BMRQ: *Emotion Evocation, Sensory-Motor, Mood Regulation, Musical Seeking, Social Reward*
- Block 4: Averaged *EDM Stimuli Liking* for the four EDM fragments or *Beat Stimuli Liking* for the beat track, depending on the regression model.

An additional stepwise regression model was built, with the BMRQ Sensory-Motor subscale as the dependent variable. This was done to test whether the self-reported tendency to move to music (measured through the Sensory-Motor subscale from BMRQ) can be explained by trait empathy and/or personality traits. Similarly to the previous two analyses, a combination of the stepwise and sequential approaches was used. Personality traits were tested in Block 1, while the subscales of trait empathy were tested in Block 2.

Finally, to test for potential differences between male and female participants, t-tests were performed for the average of the EDM and beat segments from the two listening sessions, as well as for the Sensory-Motor subscale of the BMRQ. Also, potential differences between musically trained and non-trained participants were explored through t-tests, in which musically trained participants were defined as those who had more than two years of musical training ($N = 19$).

Results

When it comes to QoM in response to EDM, in the blockwise regression analyses of significant predictors (using the stepwise method), only Empathic Concern (a subscale of trait empathy; Block 2) emerged as a significant predictor of average QoM in response to EDM ($Beta = .384$, $t = 2.35$, $p = .025$). Thus, only Empathic Concern was entered into the final regression model. The model explained 12.1 % of the variance (adjusted R square; $F(1,32) = 5.526$, $p = .025$).

Similarly, QoM to the beat segment was explained only by Empathic Concern ($Beta = .365$, $t = 2.44$, $p = .021$), and the model explained 13% of the variance (adjusted R square; $F(1,32) = 5.936$, $p = .021$). The Spearman correlations between all independent and dependent variables are displayed in Table 5.

Since the Stepwise-method is associated with an inflated likelihood of Type 1 errors (i.e., false positives), we also carried out two confirmatory regression analyses using the Enter-method to explore whether Empathic Concern remains a significant predictor of QoM when all possible predictors are included in the model. Although the resulting regression models themselves were non-significant due to the high number of non-significant predictors, these analyses revealed that Empathic Concern remained a significant predictor ($Beta = .628$, $t = 2.72$, $p = .014$ for EDM; $Beta = .569$, $t = 2.38$, $p = .028$ for beat) even when all the possible predictors were included in the model. Additionally, BMRQ Musical Seeking emerged as a significant, negative predictor in both analyses ($Beta = -.584$, $t = -2.50$, $p = .022$ for EDM; $Beta =$

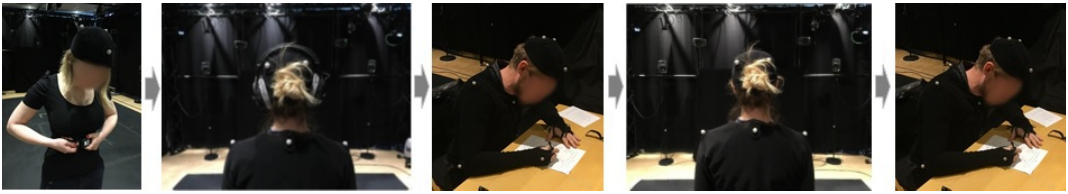

Figure 3. The different parts of the experiment (from left to right): preparation, first listening session, first set of questionnaires, second listening session, second set of questionnaires (Written informed consent was obtained from the participants for publication of images in this article).

Table 2. Means and standard deviation values for background variables. The answers to the three last questions were given on a five-point Likert scale (*Definitely not* to *Definitely yes* for "Liking to dance", *Poor* to *Excellent* for "Sense of rhythm" and *Clumsy* to *Excellent* for "Physical coordination").

Question		Mean	SD
Hours spent weekly on:	listening to music	14.90	11.55
	playing/producing/composing music	4.02	8.30
	dancing (professional, at a party, etc.)	1.15	1.94
	exercising (other than dance)	4.85	5.40
Music training:	years	5.82	7.11
	weekly hours of practice	2.37	5.32
Liking to dance		3.68	1.27
Sense of rhythm		3.76	1.02
Physical coordination		3.53	0.75

Table 3. Comparison of the average quantity of motion (QoM) and BMRQ Sensory-Motor score based on gender and musical training.

		Women			Men		
		Mean	SD	N	Mean	SD	N
QoM	EDM	7.64	1.35	18	7.29	1.29	16
	Beat	7.63	1.45	18	7.24	1.31	16
BMRQ Sensory-Motor		3.78	0.82	18	3.70	0.69	16
		Music training (>2 years)			Little or no music training (<2 years)		
		Mean	SD	N	Mean	SD	N
QoM	EDM	7.51	1.51	19	7.43	1.07	15
	Beat	7.46	1.68	19	7.43	0.93	15
BMRQ Sensory-Motor		3.86	0.74	19	3.58	0.76	15

Table 4. Standardised Beta coefficients for all variables from the regression analysis with Enter method.

	EDM			Beat		
	Beta coefficients	t	Sig.	Beta coefficients	t	Sig.
(Constant)		1.593	0.129		1.354	0.192
IRI Perspective Taking	0.162	0.894	0.383	0.111	0.564	0.580
IRI Fantasy	-0.056	-0.274	0.787	-0.012	-0.055	0.957
IRI Empathic Concern	0.628	2.722	0.014	0.569	2.382	0.028
IRI Personal Distress	-0.031	-0.122	0.904	0.087	0.321	0.752
BMRQ Emotion Evocation	-0.087	-0.310	0.760	-0.058	-0.202	0.842
BMRQ Sensory-Motor	-0.162	-0.701	0.492	-0.212	-0.865	0.398
BMRQ Mood Regulation	0.598	1.549	0.139	0.635	1.734	0.100
BMRQ Musical Seeking	-0.584	-2.501	0.022	-0.602	-2.461	0.024
BMRQ Social Reward	-0.028	-0.110	0.914	0.096	0.346	0.733
BFI Extraversion	0.097	0.480	0.637	0.154	0.717	0.483
BFI Agreeableness	-0.194	-0.861	0.401	-0.079	-0.331	0.745
BFI Conscientiousness	-0.458	-2.067	0.053	-0.392	-1.671	0.112
BFI Neuroticism	-0.294	-1.151	0.265	-0.323	-1.178	0.254
BFI Openness to Experience	0.201	1.024	0.320	0.118	0.565	0.579
Stimuli liking (EDM/Beat)	0.230	1.060	0.303	-0.002	-0.008	0.993

-.896, t = -2.46, p = .024 for beat). The coefficients for all variables in both models are shown in Table 5.

When it comes to the self-rated tendency to move to music, in a similar blockwise regression analysis of the significant predictors of the Sensory-Motor score from BMRQ, only Empathic Concern (Block 2) emerged as a significant predictor (*Beta* = .349, t = 2.11, p = .043). The model explained 12.2% of the variance (adjusted R square; $F(1,32) = 4.437$, p = .043).

A series of independent samples t-tests showed no significant differences between male and female participants, nor between musically trained and non-trained participants, in QoM or self-reported tendency to move (Table 3).

Discussion

The results of the regression analyses revealed that trait empathy, specifically the Empathic Concern scale, is a significant and moderate predictor of spontaneous movement to the stimuli. The Empathic Concern scale taps into feelings of compassion and sympathy experienced in response to the observed negative experiences of others (Davis, 1983). This empathy component has previously been linked to the enjoyment of sad and tender music (Vuoskoski et al., 2012; Taruffi & Koelsch, 2014), as well as to the intensity of music-induced emotions (Vuoskoski & Eerola, 2012; Saarikallio et al., 2012).

Our findings are in line with those of Bamford & Davidson (2017), who found that trait empathy was associated with more accurate synchronisation to musical rhythms. They postulated that empathy and rhythmic entrainment might rely on shared brain circuits, namely the human Mirror Neuron System, which has been hypothesised to play an important role in both music cognition and empathic processes (Gallese, 2001; Molnar-Szakacs & Overy, 2006; Overy & Molnar-Szakacs, 2009). Both empathy and rhythmic entrainment entail attuning to the actions and expressions of others, and involve motor resonance, either simulated or enacted (Preston & De Waal, 2002; Keller et al., 2014). Furthermore, experiencing empathy and rhythmic entrainment have both been associated with subsequent increases in social bonding and prosocial behaviour (Seyfarth & Cheney, 2013; Wiltermuth & Heath, 2009).

While the link between empathy and entrainment seems more straightforward in the context of interpersonal interaction and behavioural synchrony, it could also apply to spontaneous movement to music. Listening to music that evokes a clear sense of pulse involves a significant degree of auditory-motor resonance even in the absence of overt movement (Stupacher et al., 2013), and the areas of the brain that are involved in motor planning and execution are also engaged in beat processing (Grahn & Brett, 2007; Grahn, 2012). Thus, it could be argued that beat-induction is achieved through simulated motor action. Since trait empathy is associated with increased motor simulation when observing facial expressions (Pfeifer et al., 2008) or listening to action sounds (Gazzola et al., 2006), it is possible that high trait empathy also contributes to greater motor simulation in the context of beat processing. Indeed, in a study by Wallmark et al. (2018) both affective and cognitive forms of empathy modulated activity in sensorimotor and cognitive areas of the brain during listening to music and short musical sounds. The authors pointed out that musical sound is not an obvious social stimulus (compared to those typically used in studies on empathy), and yet it can elicit neural responses consistent with empathic processes. They suggest that studying musical experiences can provide a window into understanding social cognitive and affective processing. Similarly, Launay (2015) argues that listening to any musical sound is inevitably a social experience, and that musical engagement should be viewed as a form of social engagement.

Our results show that Empathic Concern not only predicts the amount of spontaneous movement in response to music, but also in response to the simple isochronous beat of the reference track. Compared to EDM, the simple isochronous beat is not as closely associated with genre-related behaviours, such as, dancing and clubbing. This result can be interpreted with regard to the role of empathy in processing rhythmical sounds, or with regard to sound features that are associated with movement responses. It is important to note that the reference track was made with a synthetic bass drum sound, not a standard metronome click which is typically used for reference. We decided to use a bass drum sound, since it resembles the 'flat four' pattern found in EDM tracks. In fact, it is not uncommon for EDM tracks to use such a simple bass drum beat as part of the intro section. Therefore, one could argue that the bass drum beat used in the reference track was more 'musical' than a higher-pitched metronome sound would have been. It has been shown that low-frequency energy in a musical beat intensifies body movement to music (Burger et al., 2013, 2017; Van Dyck et al., 2010; Bamford & Davidson, 2017). Moreover, Zentner & Eerola (2010) showed that infants spontaneously respond with movement not only to music, but also to simple rhythmic stimuli. Some of their stimuli were similar to the beat track used in our study, and were designed with a similar goal of making them less abstract and less distant from music by using a drum-like sound instead of a metronome click. These results suggest that a regular pulse may be more important for driving spontaneous movement responses to music than the complexity of the rhythmic stimuli (including its timbral features, syncopation, microtiming, and so on). Future studies should look more systematically into the role of different rhythmic components in spontaneous movement responses.

Furthermore, Empathic Concern also emerged as the only significant predictor on the Sensory-Motor subscale of the BMRQ questionnaire. This subscale comprises four questions:

- ”I don't like to dance, not even with music I like.” (reverse score)
- ”Music often makes me dance.”
- ”I can't help humming or singing along to music that I like.”
- ”When I hear a tune I like a lot I can't help tapping or moving to its beat.”

The consistent correlation between trait empathy and both the observed movement and the self-reported general tendency to move to music, suggests that empathy may indeed be related to this behaviour in everyday life. This limits the possibility that highly empathic participants were just motivated to provide 'satisfactory' results. The fact that they were in a motion capture lab might have prompted them to think that the researchers were expecting to observe some movement, even though the instructions were kept intentionally unclear on whether movement was expected.

Based on knowledge from the literature, we hypothesised that the amount of movement could be predicted by the participants' personality traits (McCrae, 2007; Nusbaum & Silvia, 2011; Luck et al., 2009, 2010), and Sensory-Motor oriented style of drawing reward from music (Mas-Herrero et al., 2013). None of these turned out significant in our analyses. This result is not conclusive, however, given the limitations of our study, the scarcity of previous literature on the role of individual differences in listeners' tendency to move to music, the varying paradigms used to study body movement in response to music, and the fact that most previous studies have targeted large-scale body movement. It is possible that traits such as Openness to Experience (McCrae, 2007; Nusbaum & Silvia, 2011) or Extraversion (Luck et al., 2009, 2010) are more related to other aspects of responsiveness to music than the particular one that we measured. Moreover, the relatively small sample in this experiment, when compared to the number of variables in the regression models, might have resulted in biases in giving or taking weight from specific variables. In the confirmatory regression analyses using the Enter-method, the BMRQ-subscale Musical Seeking emerged as another significant predictor of quantity of motion in response to both EDM and beat. However, the relationship between Musical Seeking and QoM was negative, meaning that the tendency to seek new music and music-related information was associated with less movement. Since Musical Seeking did not emerge as a significant predictor in the sequential stepwise regression analyses, and since the raw correlation between Musical Seeking and QoM was rather low, it may be that this variable only happened to explain a portion of the variance in QoM not explained by any of the other predictors.

Contrary to our prediction, the variables describing preference for experiment stimuli did not predict the amount of movement. The correlations between EDM stimuli liking and body movement were positive, but did not reach significance. This might, again, result from a small sample size and other limitations of the study. There are some studies suggesting that preference for the stimuli is important for ratings of groove (Senn et al., 2018, 2019) and the amount of movement during spontaneous dance (Luck et al., 2014). An alternative explanation would be that music does not need to be enjoyed to induce spontaneous movement responses. However, the enjoyment of music can modulate automatic physiological processes such as heart rate and blood pressure (Walworth, 2003), or pupillary responses to music (Gingras et al., 2015; Laeng et al., 2016). We believe that this topic is worth further investigation.

Surprisingly, musical training did not predict QoM in our study, nor the Sensory-Motor score of BMRQ. However, the self-reported measurement of musical training used in our study was fairly general, so other results could have been found with a more detailed breakdown of musical training. To conclude about the role of musical expertise on spontaneous body movement to music, a more thorough collection of data, and a larger sample of participants, is required.

Limitations

It is worth repeating that the present study is exploratory in nature and has several limitations. First of all, the sample size of participants is relatively small. Given the high number of independent variables, as well as the relatively low significance values, the results need to be approached carefully and without arriving at definite conclusions. It should specifically be noted that the stepwise method used in the regression analyses is associated with an increased likelihood of Type I errors. However, we tried to mitigate this possibility by running confirmatory regression analyses using the Enter-method, with all potential predictors included in the model. Empathic Concern remained a significant predictor of QoM also with all other predictors included. Furthermore, Empathic Concern also predicted the self-rated tendency to move to music, providing further support for a positive relationship between music-induced movement and empathic traits.

In this study, we have primarily looked at the *amount* of movement, measured as QoM from the motion capture data. While this measure tells something about how much people moved on average to the different stimuli, it does not allow us to conclude whether the observed movement is related to sensorimotor synchronisation with music and rhythm, or to other causes of movement, such as postural adjustments, intensified body sway, and so on. Future studies could aim at analysing the periodicity of the motion capture time series, and try to cross-correlate these to various continuous musical features, such as, rhythmic events, harmonic changes, melodic shapes, and spectral flux.

Another limitation of the present study is the potential effect of the laboratory context within which the study was carried out. As mentioned above, both our study and that by Bamford & Davidson (2017) employed an open-ended instruction, in which participants were allowed to respond freely to the music stimuli. However, the laboratory setting afforded movement in different ways in these two studies. In our study, the participants were standing on a balance board with multiple sensors attached to their bodies. In the study by Bamford & Davidson (2017), on the other hand, participants were not restricted by any equipment, and were able to move freely in the recording space. These two experimental paradigms allowed for different types of analyses and observations, and are also prone to different types of biases. On the one hand, letting participants decide whether they want to move to music seems appropriate for studying *spontaneous* movement responses to music. On the other hand, some aspects of the study design will inevitably be noticed by the participants, and can lead to different, perhaps even opposing, interpretations of the task by the subjects. In our study, the participants' movement responses may have been driven by whether or not they assumed that movement is expected of them. We have previously run several other experiments that have been branded publicly as "Norwegian Championship of Standstill" (Jensenius et al., 2017; González Sánchez et al., 2018, 2019). The current experiment was never branded in this way, and we explicitly excluded people that had participated in previous experiments. Still, it may be that knowledge about our previous experiments primed some participants to stand as still as possible.

Given that our current study was carried out in a highly controlled laboratory setting, it would be premature to extrapolate these data to reflect participants' general tendency to move to music. At the same time, the consistency between the results for the movement variables, and the self-reported tendency for music-induced movement (Sensory-Motor scale from BMRQ), suggests that this inference from lab-specific behaviour to a more general tendency is worthy of further investigation.

An alternative interpretation of our results could be that empathic people move more in general, independent of music. A comparison of spontaneous movement in silence and music could address this question. Unfortunately, in the present data, an analysis of movement in silence was not performed due to an unexpected bias in the data. Since we did not explain the role of the silence segments in between the music excerpts, some of our participants treated them as 'breaks', so they would occasionally adjust their posture, scratch their nose, and so on. Therefore, we decided not to use the silence fragments in the current analysis.

Yet another limitation of the current study is that it only deals with EDM tracks. This musical genre has some characteristics (steady beat, confined form, etc.) that make it difficult to generalise our findings to other types of music. Furthermore, only four EDM excerpts (from three different tracks) were included in the experiment. More systematic studies, comprising a larger collection of stimuli and a broader selection of musical genres, are needed to better understand spontaneous motor responses to music, and the musical features that drive such responses. It would also be interesting to examine movement patterns to different parts of an EDM track, such as done by Burger et al. (2017) and Solberg & Jensenius (2016).

Conclusions

The aim of this article has been to investigate the role of individual characteristics in people's spontaneous body movement responses to music. We explored whether personality traits, empathy, music-related behaviour, and liking for the experiment stimuli could predict the amount of spontaneous movement to four EDM tracks and to a simple, isochronous reference beat. We also tested whether the same variables could predict participants' self-reported tendency to move to music.

Even though there are many limitations of the experiment (as discussed above), our results suggest that there is, indeed, a link between empathy and spontaneous movement responses to music. This is in line with previous research by Bamford & Davidson (2017). Among various other listener characteristics, empathy appeared to be the single significant predictor both for observed body movement and for a self-reported tendency to move to music. The results of this exploratory research suggest that there is a link between spontaneous sensorimotor synchronisation with auditory rhythms and the affective aspect of empathy.

The experimental paradigm and the results presented in this article should be seen as a preliminary investigation of the question: ”Who is likely to move to music?”. There has been an increasing amount of studies into different types of music-related body movement in recent years, but less attention has been devoted to individual differences. We hope that this study will encourage more researchers to explore this research question, and develop more paradigms for studying spontaneous body movement to music.

Table 5. Means, standard deviations and Spearman correlations of the model variables. ** indicates significance at the $p < 0.01$ level and * at the $p < 0.05$ level.

Variable	M	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Body EDM	7.48	1.32																		
2. Body Beat	7.45	1.38	0.91**																	
3. BFI Extraversion	3.18	0.70	0.05	-0.01																
4. BFI Agreeableness	3.78	0.46	0.04	0.09	-0.09															
5. BFI Conscientiousness	3.67	0.59	-0.24	-0.20	0.26	-0.07														
6. BFI Neuroticism	2.79	0.75	0.07	0.03	-0.42*	0.20	-0.38*													
7. BFI Openness	4.03	0.43	0.02	-0.07	0.09	0.21	0.35*	0.09												
8. IRI Perspective Taking	2.76	0.65	0.15	0.09	-0.11	0.12	-0.12	0.11	0.01											
9. IRI Fantasy	2.30	0.71	0.18	0.27	-0.07	0.19	-0.19	0.26	-0.01	0.07										
10. IRI Empathic Concern	2.61	0.61	0.40*	0.34	0.11	0.14	0.08	0.36*	0.23	0.11	0.30									
11. IRI Personal Distress	1.54	0.67	0.02	0.08	-0.38*	0.12	-0.42*	0.61**	-0.16	0.12	0.25	0.07								
12. BMRQ Emotion Evocation	3.92	0.77	0.11	0.17	0.25	0.27	0.04	-0.02	0.10	0.20	0.43*	0.22	0.27							
13. BMRQ Sensory-Motor	3.74	0.75	0.23	0.27	0.16	-0.01	-0.15	0.02	-0.22	0.18	0.28	0.34	0.12	0.44**						
14. BMRQ Mood Regulation	4.08	0.69	0.22	0.31	0.07	0.50**	-0.19	0.21	-0.04	0.11	0.44**	0.18	0.42*	0.68**	0.48**					
15. BMRQ Musical Seeking	3.54	0.93	-0.11	-0.09	0.27	0.30	0.03	0.12	0.21	0.14	0.20	0.23	0.18	0.40*	0.26	0.58**				
16. BMRQ Social Reward	3.79	0.72	0.06	0.21	-0.03	0.39*	0.12	0.30	0.13	0.03	0.43*	0.34	0.29	0.45**	0.44**	0.54**	0.51**			
17. Stimuli liking EDM	4.60	0.94	0.18	0.28	-0.02	0.22	-0.18	0.24	-0.15	0.11	0.16	-0.10	0.33	0.24	0.30	0.59**	0.27	0.24		
18. Stimuli liking Beat	2.03	1.17	0.11	0.02	0.21	0.10	-0.03	-0.13	0.15	-0.15	0.10	0.05	-0.13	0.17	0.22	0.20	0.20	0.05	0.20	

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Appendix

The oral instruction given to subjects before the experiment:

> Please stand on the force platform in a relaxed, comfortable position with your arms at the sides of your body. Try to remain in this neutral position during the experiment. Keep your eyes on the white cross on the wall. You will hear some rhythms and music, with periods of silence between them, and the experiment will last about 8 minutes. We will start with 30 seconds of silence. Are the instructions clear?

Paper V

Standstill to the ‘beat’: Differences in involuntary movement responses to simple and complex rhythms

Agata Zelechowska, Victor E. Gonzalez-Sanchez, Alexander Refsum Jensenius

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Standstill to the 'beat': Differences in involuntary movement responses to simple and complex rhythms

Agata Zelechowska*
RITMO Centre for Interdisciplinary Studies in Rhythm, Time and Motion
Department of Musicology,
University of Oslo
agata.zelechowska@imv.uio.no

Victor Gonzalez Sanchez
RITMO Centre for Interdisciplinary Studies in Rhythm, Time and Motion
Department of Musicology,
University of Oslo
v.e.g.sanchez@imv.uio.no

Alexander Refsum Jensenius
RITMO Centre for Interdisciplinary Studies in Rhythm, Time and Motion
Department of Musicology,
University of Oslo
a.r.jensenius@imv.uio.no

ABSTRACT

Previous studies have shown that movement-inducing properties of music largely depend on the rhythmic complexity of the stimuli. However, little is known about how simple isochronous beat patterns differ from more complex rhythmic structures in their effect on body movement. In this paper we study spontaneous movement of 98 participants instructed to stand as still as possible for 7 minutes while listening to silence and randomised sound excerpts: isochronous drumbeats and complex drum patterns, each at three different tempi (90, 120, 140 BPM). The participants' head movement was recorded with an optical motion capture system. We found that on average participants moved more during the sound stimuli than in silence, which confirms the results from our previous studies. Moreover, the stimulus with complex drum patterns elicited more movement when compared to the isochronous drum beats. Across different tempi, the participants moved most at 120 BPM for the average of both types of stimuli. For the isochronous drumbeats, however, their movement was highest at 140 BPM. These results can contribute to our understanding of the interplay between rhythmic complexity, tempo and music-induced movement.

CCS CONCEPTS

• **Applied computing** → *Sound and music computing*; **Psychology**.

KEYWORDS

Music, Rhythm, Movement, Motion Capture, Groove

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Figure 1: A group of participants ready to stand still. Each participant wears a motion capture marker on top of their head. A reference marker placed on a tripod can be seen in between the participants. Two speakers in front of the participants were used for sound playback.

1 INTRODUCTION

Music and movement are so deeply connected that they can be considered an 'ancient marriage' [22]. Not only is body movement required to produce music (unless the process is fully moved to the digital realm), but also listening to music can create an *urge* to move [11]. Recent studies have shown that music can increase body movement even when people try to stand still [8, 9, 13]. These findings not only confirm the common belief that 'music moves us', but also show that movement to music can be involuntary. Moreover, previous studies have shown that particularly music with clear rhythmic patterns, such as electronic dance music (EDM), has movement-inducing properties [8]. This is in line with several other studies that have shown that rhythmic features have a particularly strong influence on body movement [4, 5, 31], and on the feeling of groove, i.e., an urge to move [11, 17, 21, 30].

Several studies indicate that an optimal rhythmic complexity, which is neither too simple nor too unpredictable, is crucial for inducing the sensation of wanting to move [17, 23, 30, 31]. However, a study in which actual movement was measured showed

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that free movement of hands and torso is fairly similar in terms of acceleration and synchronisation for rhythms of low and medium complexity [31]. Still, the lowest possible level of rhythmic complexity, such as in simple isochronous beats of a metronome—i.e., sequences of beats occurring at equal time intervals—should have a smaller movement-inducing effect than regular music. Contrary to this assumption, Zentner and Eerola [33] found that infants spontaneously moved to isochronous drum beats as much as they did to rhythmic music, and more than to rhythmic speech.

Studies on adults have shown mixed results when comparing movement to music and isochronous streams of sounds (most often, sounds of synthetic or acoustic metronomes). Both types of stimuli are often used as cues in research on motor rehabilitation, but typically either music or metronome stimuli are used without comparison [1, 20]. Studies on healthy populations have shown that music, compared to metronome cues, increases stride length and walking speed [25, 32]. On the other hand, it has also been found that metronome cues work better than music when people try to synchronise their steps to the beat while walking [15]. Thus, there seems to be little consensus on the effects of music and metronome-like sounds on body movement in the literature.

The use of metronomes for comparing the impact of simple rhythms with more complex rhythmic stimuli might result in biases. Metronome sounds are usually relatively high in pitch, whereas music used in movement studies usually contains a wider frequency range. Some studies indicate that low-frequency sound can increase the intensity of movement, as well as the quality of the synchronisation with the beat [3, 24, 28]. In the case of simple auditory rhythms, it has been shown that using a low-pitched metronome sound (100 Hz) results in higher movement intensity and better synchronisation with sound compared to that of a metronome with a higher pitch (1600 Hz) [29]. This can be explained by the superior time perception for lower musical pitch [10]. Moreover, the functioning of the vestibular system in the inner ear is particularly sensitive to stimulation with low-frequency sound, and is associated with sensations of body movement [26, 27]. Therefore, it seems more appropriate to use low-frequency sounds, such as the sound of a bass drum, when comparing the effects of simple isochronous rhythms with those of more complex rhythmic stimuli or music [33]. Natural drum sounds often have timbral and dynamical qualities that make them perceptually more similar to music than a plain metronome. Moreover, drums are often associated with body movement. In some cultures it is common to dance to the sound of drums alone, such as to the Japanese taiko [26]. To our knowledge, this type of music has not been used so far in studies on body movement.

Finally, there is evidence suggesting that the tempo of musical stimuli is crucial for inducing movement. Studies on groove showed that the optimal tempo for eliciting sensation of wanting to move is within the range 100–120 BPM [6, 11]. However, other studies suggest that tempo plays little role in the feeling of groove [17]. The preferred tempo for movement can depend on the type of movement. For dancing, on average people prefer a tempo around 125–130 BPM [19], while for walking, a tempo of 110–120 BPM is preferred [25]. Some researchers point out that the natural walking tempo, which on average is around 120 BPM [16], is similar to the tempo of dance and music. An evolutionary explanation of this can be that bipedalism contributed to the development of various rhythmic behaviours and organisation of sensory-motor circuits in the brain [14, 26]. One could speculate that tempi in the range 110–130 BPM should have particularly strong movement-inducing properties. However, the role of rhythmic tempo on inducing body movement when standing is still unknown.

In the present study, we examine the impact of complex drum patterns and isochronous drumbeats (in three different tempi) on involuntary movement responses to music, in a task where participants are asked to stand as still as possible. Based on knowledge from the literature, we hypothesise that:

1. there will be more involuntary movement in the sound condition (both isochronous and complex drum patterns) than in the silence condition,
2. the complex drum patterns will induce more involuntary movement than the isochronous drumbeats,
3. the stimuli at 120 BPM will induce more involuntary movement than the stimuli at 90 BPM and 140 BPM, for both isochronous and complex drum patterns.

2 METHODS

2.1 Participants

The experiment took place during the University of Oslo "Open Day" in March 2019, advertised as "The Nordic Championship of Standstill". The participants included students and staff from the University, but also other interested people from the larger Oslo area. A prize of 1000 NOK was offered to the participant with the lowest captured motion. Participation was open to everyone, but those who met the exclusion criteria were excluded from the analysis: age under 18 years old, participation in earlier editions of the experiment, hearing loss or balance disorder. The final dataset used for the analysis consisted of 98 participants (41 female, 57 male, average age: 24.6 years, SD: 8.8 years).

The participants were asked to report on the hours per week spent on listening to music (15.9 hours, SD: 14.5), creating music (3.9 hours, SD: 9.2), dancing (1.9 hours, SD: 2.3), and exercising physically (4.2 hours, SD: 3.8). All participants gave their informed consent prior to the experiment, and they were allowed to withdraw from the study at any point in time.

2.2 Motion capture

An eight-camera optical, marker-based, infrared motion capture system (Optitrack Flex 100) was used to track the instantaneous 3D position of a reflective marker placed on the top of each participant's head at a sampling rate of 120 Hz. It has previously been shown that the spatial noise level of such motion capture system is considerably lower than that of human head sway during standstill [2, 12]. Position data was recorded and pre-processed in OptiTrack Motive, and further analysis was done in Python and SPSS Statistics.

2.3 Sound stimuli

The six sound stimuli consisted of three isochronous drumbeats (Isochronous) and three custom-made complex drum patterns (Complex).[1] Each set was played at different tempi (90, 120, 140 BPM).

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[1] The stimuli are openly available under DOI: http://doi.org/10.5281/zenodo.3970991

The spectrograms in Figure 2 show the differences in tempo and overall density of the six tracks.

All stimuli were produced with samples from an openly available database of acoustic drum recordings.[2] Each of the three isochronous drumbeat tracks was based on a single drum sample, looped over 30 seconds. We ended up using a different drum sample for each of the three tracks to ensure that the timbral qualities of the drum sounds were preserved. This was decided on after initial testing with time stretching and pitch shifting of the samples, which resulted in audible artefacts. Since the original samples were slightly different between tempi, the final isochronous tracks ended up with some pitch and timbre differences, as can be seen in the chromagrams in Figure 4. It should also be noted that most of these samples are recorded from bass drums, thus they have a fairly low fundamental frequency and a long attack time (see the close-up of the waveform in Figure 3). We deliberately wanted such a rich and full bass drum sound for the isochronous drumbeats, instead of a sharper high-frequency metronome-like sound.

As for the complex drum patterns, these were produced based on short two-bar sequences of different types of drums in various tempi from the same database as mentioned above. The aim was to create drum patterns with a certain level of timbral and rhythmic complexity, rather than synthetic, highly controlled arrangements of isolated drum sounds. Again, we experimented with time stretching and pitch shifting recordings at different tempi, which ended up sounding unnatural. Thus, there are differences between the produced tracks because of the differences in samples used. The final tracks have qualities similar to those of the Japanese taiko drum playing, with rhythmic patterns that are neither too simple nor too complex. The different pitches of the drums and the richness of their timbres can easily be seen in the chromagrams in Figure 4.

The stimuli were played to the participants at a comfortably loud volume using two Genelec 8020 loudspeakers mounted on a rig between the ceiling and the wall facing the participants (see Figure 1). The distance between the speakers and the heads of the participants in the first row was approximately 1.5 meters. The speakers were mounted in such way that none of the participants stood directly in front of a speaker.

2.4 Procedure

The participants were recorded in groups of 4–8 people at a time. The uneven group distribution was caused by the availability of people throughout the day of the experiment. The distribution of participants in the laboratory was standardised across trials, with marks on the floor indicating the positions where people could stand. After choosing one of the marked spots on the floor, participants signed the consent forms and were instrumented with a single motion capture marker on top of their heads. Next, they were introduced to the study, and asked to stand as still as possible during the seven-minute long recording session, being free to choose their own standing posture. All participants faced in the same direction (see Figure 1).

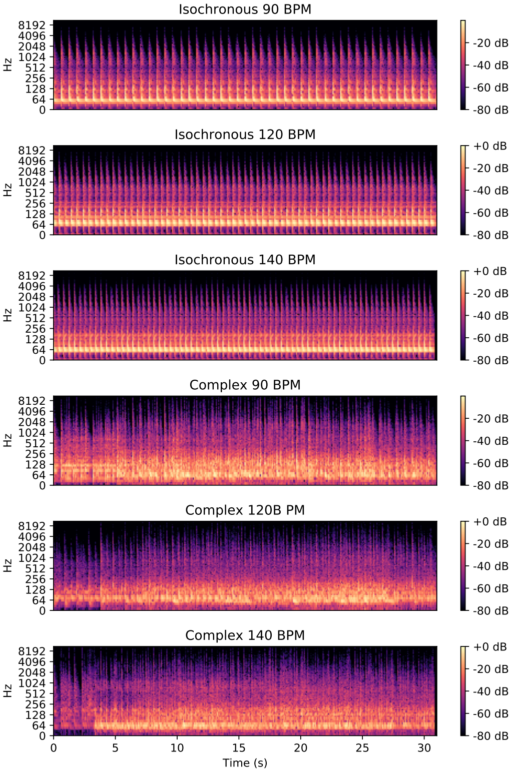

Figure 2: Spectrograms of each of the six sound stimuli, showing the differences in tempo and rhythmic complexity between the tracks.

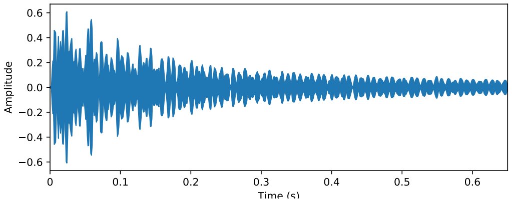

Figure 3: A closer look at the waveform of one of the drum sounds used in the isochronous pattern reveals some of the richness of this bass drum sound.

During the recording session, the participants were exposed to silence and sound in alternating order. Each trial began and ended with 45 seconds of silence, with alternating segments of 30 seconds of sound (approximately, as the samples were cut to the bar) and 30 seconds of silence in between. Thus, a complete sequence consisted of: Silence, Stimuli1, Silence, Stimuli2, Silence, Stimuli3, Silence,

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[2] https://www.musicradar.com/news/sampleradar-260-free-tribal-adventures-samples

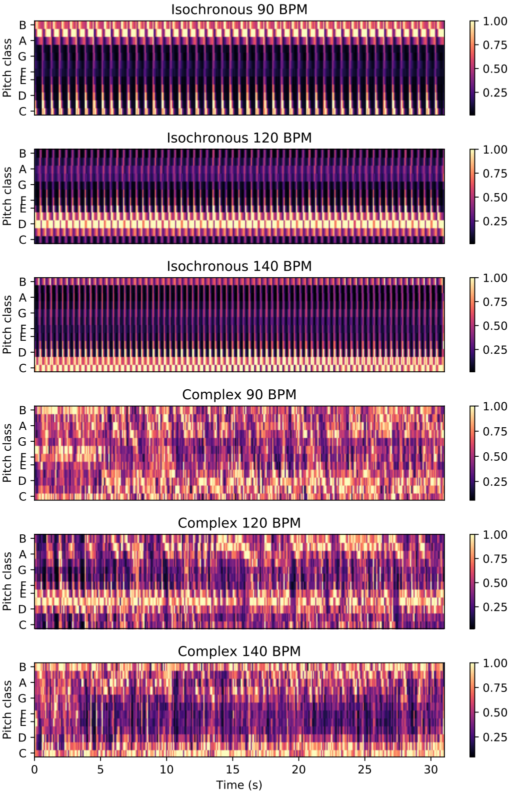

Figure 4: Chromagrams of the six stimuli reveal some pitch differences in the tuning of the drums. Since different samples were used (without pitch shifting), they have different pitches. The calculation is done using the `librosa.feature.chroma_cqt` function from Librosa [18], with a hop size of 512 samples.

Stimuli4, Silence, Stimuli5, Silence, Stimuli6, and Silence. The six sound stimuli were played in random order for each trial.

After the experiment, participants were asked to fill in a short set of questionnaires, which are not a subject of analysis in the present paper. The whole experiment session for each group lasted for approximately 30 minutes.

2.5 Analysis

As in our previous studies, the head sway of each participant was measured as the quantity of motion (QoM) of their respective reflective marker. This was computed as the first derivative of the position time series:

$$QoM = \frac{1}{T}\sum_{n=2}^{N} \parallel p(n) - p(n-1) \parallel$$

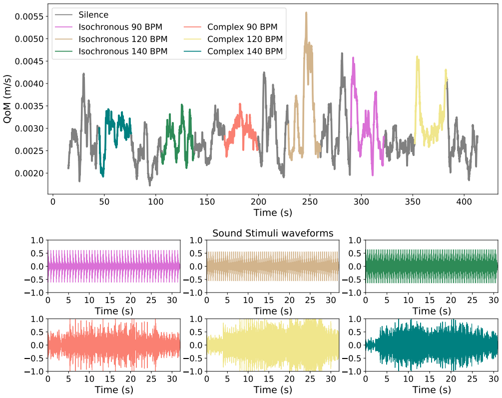

Figure 5: Waveforms of the auditory stimuli (bottom) and segmented QoM time series (top) showing the complete experiment data from one participant.

where p is the 3D position of a marker, N is the total number of samples and T is the total duration of the recording. Instantaneous QoM was obtained for each participant for the whole trial and subsequently segmented by stimulus for further analysis (see Figure 5). Thus, the complete data set consisted of 1274 QoM time series (116 participants x 13 segments). The position data of one marker attached to a tripod located at the centre of the capture volume was used to control for sound-induced and other types of artifacts in the motion data.

Mean QoM values were compared between conditions (sound stimuli and silence) using a paired-sample t-test, while a two-way repeated measures analysis of variance (ANOVA) was used to measure the effects of type of stimulus (isochronous and complex patterns) and tempo (BPM) on QoM. Analyses of the audio tracks were done with Librosa [18].

3 RESULTS

The head sway paths from a representative trial for one subject (Figure 6) show that people do, indeed, move continuously while trying stand still, yet at a very small scale. The influence of condition (silence vs sound stimuli) on QoM was assessed by computing the average QoM for segments of silence and segments of sound stimuli. The average QoM for the sound condition was 9.39 mm/s (SD = 2.64 mm/s), while the average QoM for the silence condition was 8.70 mm/s (SD = 2.71 mm/s). A paired-samples t-test revealed that these differences were statistically significant ($t(97) = 9.45$, $p < 0.001$). The differences were also significant when comparing the silence segments with the Complex stimuli ($t(97) = 11.26$, $p < 0.001$) and with Isochronous stimuli ($t(97) = 4.67$, $p < 0.001$) separately.

Mean and standard deviation values for QoM to each of the sound stimuli are displayed in Table 1. A two-way ANOVA revealed that there was a significant main effect of the type of sound stimulus on the participants' quantity of motion, which was higher to the Complex stimuli (F(1,97) = 22.08, p > .001, η_p^2 = .185). The main

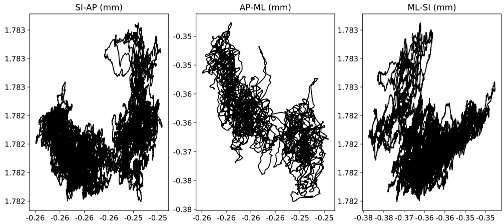

Figure 6: Example head movement exhibited by one participant for a complete trial (7 minutes) in the superior-inferior (SI), anterior-posterior (AP), and medial-lateral (ML) directions.

Table 1: Means and standard deviations of quantity of motion for all stimuli, and for the sound and silence conditions.

Track	Tempo (BPM)	Mean QoM (mm/s)	SD QoM (mm/s)
Isochronous	90	8.74	2.72
Isochronous	120	9.24	2.70
Isochronous	140	9.46	3.15
Complex	90	9.06	2.67
Complex	120	10.50	3.27
Complex	140	9.32	2.73
Sound	—	9.39	2.64
Silence	—	8.70	2.71

effect of tempo on QoM was also significant (F(2,194) = 31.66, p > .001, η_p^2 = .246). Highest QoM was observed to the sound stimuli at 120 BPM. Furthermore, there was a significant interaction between the type of stimulus and tempo (F(2,194) = 13.91, p > .001, η_p^2 = .125). For the Complex stimuli, the largest movement was at 120 BPM, while for the Isochronous stimuli the largest movement was observed at 140 BPM. Figure 7 displays the interactions between the type of stimulus and tempo, with respect to QoM.

4 DISCUSSION

The results show that both the complex drum patterns and the isochronous drumbeats appear to have movement-inducing properties. Compared to the silence condition, participants moved more to both types of sound stimuli. This is in line with our previous findings, which showed more involuntary movement to rhythmic music than silence [8, 9, 13]. It also corroborates findings that both isochronous drumbeats and rhythmic music induce spontaneous movement responses in infants [33].

When comparing the two types of sound stimuli, we found that the complex drum patterns induced more involuntary movement than the isochronous drumbeats. Previous studies suggest that rhythmic patterns should not be too simple, but also not too complex, in order to induce feelings of wanting to move to music [17, 23, 30]. Our findings fit well into this narrative. However, in another study [31], free movement of hands and torso did not differ when performed to stimuli of low and medium rhythmic complexity. These findings seem to oppose our results, but it should be noted that this and the present study examined different types of movement behaviour (free movement versus involuntary movement during standstill), and used different types of rhythmic stimuli. In particular, the low-complexity stimuli used by Witek et al. [31] included a weak degree of syncopation, while our low-complexity stimuli was an isochronous beat pattern. Furthermore, some previous studies showed that music, compared to metronomes, has a stronger impact on walking [25, 32], while others produced the opposite result [15]. Our present findings indicate that, at least for spontaneous movement responses to sound, more complex rhythmic stimuli have more movement-inducing properties than simple isochronous beats.

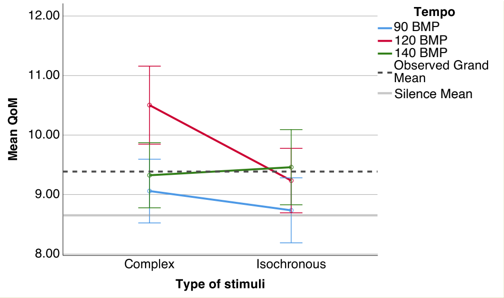

Figure 7: Interactions between the type of stimulus and tempo, with respect to quantity of motion. Error bars represent the 95% confidence interval (CI).

For both types of sound stimuli, tempo appears to have a significant impact on the level of movement. We observed significantly more movement to the average of both sound stimuli at 120 BPM than at 90 BPM or 140 BPM. This fits well with studies indicating that we are particularly sensitive to rhythms at around 120 BPM, because it matches the natural tempo of human locomotion, which shaped the evolution of sensory-motor circuits in the brain [14, 26]. It also to some extent aligns with studies on the influence of tempo on the feeling of groove [6, 11] and preferred tempo for dance [19]. However, when investigating each of the two types of sound stimuli separately, 120 BPM was the most movement-inducing tempo only for the complex drum patterns, whereas for the isochronous drumbeats, it was 140 BPM. This result is surprising, and goes against our hypothesis. One reason for this finding could be that the very fast, repetitive stimuli had a discomforting or disorienting effect, which led to more fidgeting and more head movement. Another explanation could be that the participants involuntarily moved their head to the beats, and given that at 140 BPM tempo there are more beats per minute than in 90 or 120 BPM, there was also more head movement. However, that was not the case for the complex drum patterns. Perhaps the differences between the impact of tempo between the two stimuli types are due to the design of the stimuli between different tempi? In the case of the isochronous drumbeats, it may be that the drum sound used to produce the 120 BPM stimulus had more movement-inducing properties than the sounds used in the 90 BPM and 140 BPM stimuli. It is also possible that among the complex drum patterns, the 120 BPM stimulus was unintentionally produced in a way that gave a stronger urge to move than the stimuli at the two other tempi. When producing the complex stimuli, the use of syncopation and other sound features related to rhythmic complexity was not thoroughly controlled. All stimuli were designed by ear, without following a systematic pattern that would be identical for the three tracks.

This brings us to the issue that can be considered both a limitation and an advantage of this study. Our goal was to include stimuli that felt ecological to the participants, something that they could have heard in everyday life. For this reason, we employed prerecorded sounds of real drums. We tried to produce the drum stimuli in a way that would resemble music played by Japanese taiko drummers. Such music is associated with large, dynamic movements of the body, and is performed with a dance-like choreography. According to the motor-mimetic theory, we spontaneously associate the sounds we hear with the movement they resulted from [7]. Our aim was to try to induce movement in the participants with these naturalistic sounds associated with drum playing. Moreover, the drum sounds used in the stimuli had a more complex timbre as well as more low-frequency content. This was intentional, as previous research suggests that low-frequency sounds stimulate the vestibular system [26, 27], and increase the urge to move and the intensity of actual movement [3, 24, 28, 29]. However, the fact that we used drums of different frequencies when designing the stimuli (and particularly the isochronous drumbeats stimuli, in which only one drum was playing at a time), can be seen as a limitation. Our rationale was to pick drum samples that sounded well, and that would not bore the participants. It was beyond the scope of this paper to record our own, controlled drum samples, but this could be one approach to overcome such a limitation in future studies.

Last but not least, the potential influence of the group setting on body movement was not examined in this study, which can be seen as a limitation. It is possible that there were certain collective dynamics within groups of participants that influenced how much they moved. For example, the level of motivation to win the competition exhibited by a fellow participant could have influenced the attitude of the other people in the group towards the standstill task. At the same time, individuals can differ in terms of how easily they are affected by feelings and attitudes of others, for example depending on their level of empathy trait. It is also possible that seeing another person moving could have influenced the movement of a participant. Thus, it could be argued that the participants in the second row were able to see the participants standing in front of them, but not vice versa. In future studies, it would be interesting to take into account shared and individual experiences of movement that could influence the actual movement, and to experiment with the positioning of participants within the recording space.

5 CONCLUSIONS

In this study we compared the effects of simple isochronous drumbeats and complex drum patterns, produced with naturalistic drum sounds, on involuntary movement responses to music. We observed more head movement to both types of stimuli than in silence, as well as more movement to the complex drum patterns than to the isochronous drumbeats. These results fit well with previous findings about the movement-inducing properties of music. They also correspond with some previous findings on higher influence of music on body movement compared to simple isochronous rhythms, although there is little consensus on that topic in the literature. Furthermore, we showed that participants on average moved most to the music stimuli at 120 BPM. This supports the hypothesis of a particular 'resonating' frequency of spontaneous human body movement. However, contrary to our expectation, we found that the 140 BPM drumbeats were most movement-inducing among the isochronous beats. It would be interesting to study the effects of tempo differences between simple and complex rhythmic patterns on spontaneous body movement further in follow-up studies.

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Appendices

Appendix A

Experiment instructions

Scripts for the instruction read by an experimenter before the motion capture recording sessions.

A.1 Championship of Standstill

Welcome to the Norwegian Championship of Standstill, which is also a small research experiment. The aim is to study how still people can stand, as well as how music influences standstill. We will measure your level of standstill through a motion capture system. You will place a small marker on your head. We use it to record your motion with an infrared camera system. It is completely harmless. We will measure your micromotion by calculating how many millimetres you move per second. The one with the lowest average measurement will be the Norwegian champion, and will win a 1000 kroner gift card. The experiment lasts for 8 minutes. It will start with a countdown followed by a beep. The task is to stand as still as you can. You will hear alternating sections of music and silence. The experiment will end with a signal tone. Please quit the experiment immediately if you at any point in time feel ill. Sit down carefully, or find another comfortable position, as quietly as possible, so as to not disturb the others. Is the instruction clear?

A.2 Headphones/Speakers Experiment

Please stand on the force platform in a relaxed, comfortable position with your arms at the sides of your body. Try to remain in this neutral position during the experiment. Keep your eyes on the white cross on the wall. You will hear some rhythms and music, with periods of silence between them, and the experiment will last about 8 minutes. We will start with 30 seconds of silence. Is the instruction clear?