Universiteit Gent
Faculteit Letteren en Wijsbegeerte
Vakgroep Kunst-, Muziek- en
Theaterwetenschappen

Effects of music-based biofeedback on walking and running

Jeska Buhmann

Proefschrift voorgelegd tot het behalen van
de graad van Doctor in de Kunstwetenschappen
Academisch jaar 2017-2018

UNIVERSITEIT
GENT

Universiteit Gent
Faculteit Letteren en Wijsbegeerte
Vakgroep Kunst-, Muziek- en
Theaterwetenschappen

Promotor:	Prof. Dr. Marc Leman
Doctoraatsbegeleidingscommissie:	Prof. Dr. Simone Dalla Bella Dr. Edith Van Dyck
Examencommissie:	Prof. Dr. Marc Boone (voorzitter) Prof. Dr. Ir. Leon van Noorden Prof. Dr. Pieter-Jan Maes Prof. Dr. Dirk Declercq Prof. Dr. Simone Dalla Bella Dr. Edith Van Dyck Dr. Micheline Lesaffre Dr. Luc Nijs

Universiteit Gent
Faculteit Letteren en Wijsbegeerte
Vakgroep Kunst-, Muziek- en Theaterwetenschappen
IPEM - Instituut voor Psychoacoustica en Electronische Muziek
De Krook, Miriam Makebaplein 1, B-9000 Gent, België
Tel.: +32 (0)9 264 42 77

Proefschrift voorgelegd tot het behalen van
de graad van Doctor in de Kunstwetenschappen
Academisch jaar 2017-2018

Acknowledgement

In the late summer of 2013 I found myself sitting in the garden, thinking, “Yes, I would definitely like to do scientific work again!”. Although I was not looking for a full-time job at the time, I came across a job opportunity when checking out the website of the former scientific department I had worked some 10 to 12 years before. I thought about it for less than five minutes and decided to go for it. By October 1st I was on a TGV to Montpellier with two brand-new colleagues to join the first meeting of the European BeatHealth project I would work on for the next three years.

I would like to thank Prof. dr. Marc Leman for making me a member of the IPEM team and having faith in me being a decent musicology researcher, not having a musicology background. Over the past few years my belief only grew stronger that doing research is what I love to do best, and for that I am forever grateful. The talks we had usually had an open and explorative character, opening even more doors in my brain into the unknown. Nevertheless, they were always inspiring and giving me positive energy to go on. The different ThinkTanks at IPEM had a similar effect on me. I thoroughly enjoyed the interdisciplinary talks and discussions.

Sincere thanks also go to Jean-Pierre Martens. In the past, I enjoyed working as a member in his speech lab team. And in the end, this work experience lead to the research opportunity at IPEM. In the first two years, we sat down several times to discuss the progress of my work and he helped out to settle software version differences within the machine learning code I proceeded to work on.

I also would like to thank all of my IPEM colleagues. Working at IPEM is teamwork in its truest form. From complementing each other’s work to co-authoring papers and book chapters. Thanks Dr. Edith Van Dyck, your positive attitude towards everything is contagious! Every time I envisioned something as a mountain of work you reduced it to a couple of simple subtasks, just like that. It’s a delight to share an office room with you (that includes an open-office room). And not to forget, thanks Edith and Bart Moens for making me welcome at IPEM straight from the start when we travelled together to Montpellier on my first day of work. I’m also grateful to Bart for the many work-related and non-work-related talks.

Thanks also to Ivan Scheepers, IPEM’s MacGyver, for helping out with any-

thing that needed to be developed, tested or fixed. Your help in avoiding wireless radiation (including microwaves) was invaluable and your sharp humour brought many (laughing) tears to my eyes. Thank you for that. A big thank you goes out to all the rest of my colleagues at IPEM (you know who you are) and the BeatHealth team.

In addition, I'd like to thank the members of my band (Danny, Willy, Wouter, Davey) for many fun evenings in our rehearsal room, my best friends (Annemarie, Kathy, Debby, Vivian) for their friendship, dancing and support. They made sure I did not work all the time! This also holds true for my family. Because of them I was not tempted to work in the evenings (with some occasional exceptions), so I could start working with fresh energy each morning. Thanks mom and dad (and parents-in-law), for your love and babysitting. And the biggest thank you of all goes out to my husband Mark and my lovely daughters Arwen and Mila-Lena. You make life and work fun. Love you.

Ghent, September 2017
Jeska Buhmann

Table of Contents

List of Figures

List of Tables

List of Acronyms

ANOVA	Analysis of Variance
BMRI	Brunel Music Rating Inventory
BPM	Beats Per Minute
IBI	Inter-Beat Interval
IPEM	Institute for Psychoacoustics and Electronic Music
KS	Kolmogorov-Smirnov
LRC	Locomotor-Respiratory Coupling
PACES	Physical Activity Enjoyment Scale
PCC	Pearson Correlation Coefficient
PD	Parkinson's Disease
RAS	Rhythmic Auditory Stimulation
RMSE	Root Mean Square Error
RPE	Rating of Perceived Exertion
SPM	Steps Per Minute
TLV	Threshold Limit Value
TTE	Time to Exhaustion

Glossary

Music related items

Beat	The beat is the basic measure of time in music. Beats are the salient moments in a musical piece and are usually produced by a bass and/or drum.
Tempo	This is a term that refers to the basic tempo of music or movement and is typically expressed in number of beats or steps per minute. The tempo of a musical piece can either be fast or slow.
Rhythm	Where the beat is the basic measure of time, rhythm is the pattern of music in time. The rhythmic structure characterizes the style of music. Two musical pieces can have different tempi, but the same rhythm and vice versa. In this thesis the emphasis is on the coupling of the musical tempo (indicated by the beats) with the movement tempo (indicated by the footfalls), but different rhythms are expected to influence movement patterns as well. For example, a sound in the middle of two beats, might help to emphasize lifting of the knee while walking.

Tempo related items

Tempo	A term that refers to the basic tempo of music or movement and is typically expressed in number of beats or steps per minute.
Cadence	Same as *tempo*, but only used for movement (walking and running) and not for music. Expressed in steps per minute.
Step frequency	This term is a synonym for *cadence* or *tempo*. Although frequency is normally expressed in Hz (number of recurring events per second), when it concerns

	walking or running a more common unit is the number of steps per minute.
Self-paced	This term is used to indicate a self chosen *tempo* of walking or running, also referred to as comfort tempo. A self-paced tempo is expressed in steps per minute.

Kinematic related items

Kinematics	Kinematics is the quantitative description and analysis of movement. In this thesis it concerns the movement parameters of the lower legs while walking or running.
Cadence	The tempo of walking or running in steps per minute. Synonyms are: *tempo*, *pace* and *step frequency*.
Step size or length	This is the distance that is covered from the initial contact of one foot with the ground to the initial contact of the next foot.
Stride length	This is the distance that is covered from the initial contact of one foot with the ground to the next initial contact of the same foot. If we assume that the left step length is equal to the right step length, stride length is double the step length.
Speed	Indicates how fast someone is walking or running, expressed in km/h or m/s. It is calculated by deviding the total distance travelled by the total duration of the walk or run. Although technically the term *velocity* is not the same, in this thesis speed and velocity are used interchangeably.
Velocity	See *speed*.

Other movement or training related items

Gait	This is the pattern or the way in which a person or animal walks: how the limbs move during locomotion.
Intensity	With intensity of an exercise we refer to how hard it is for someone to do the exercise. This can be measured objectively through the heart rate or subjectively by asking people to rate how they perceive the intensity. The perceived level of intensity varies per person and is determined by factors depending on the type of

	exercise. For running, the main factors affecting intensity are speed and duration of the run. For doing weight lifting the number of repetitions and the total weight are influencing factors.
Performance	In this thesis we use this as a general term to refer to how well, often or healthy someone is moving or exercising. Therefore performance can have different meanings, e.g. speed, endurance, training quantity, or a certain gait pattern.
Vigor	The use of more vigor in our movements is mentioned in this thesis when we talk about an increase in power. Power is expressed by the amount of work within a certain time frame. When the cadence stays stable, an increase in power is achieved by taking longer steps (i.e. an accelaration of the leg swing).

Nederlandse Samenvatting –Summary in Dutch–

In het eerste hoofdstuk van dit proefschrift wordt een algemene introductie gegeven van ons werk omtrent muziek-gebaseerde biofeedback voor wandelen en (hard)lopen. We bespreken de sterke koppeling tussen muzikale ritmes en bewegingsritmes en hoe deze link ingezet kan worden om alledaagse ritmische bewegingen zoals wandelen en (hard)lopen te verbeteren en te beïnvloeden. We bespreken ook het belang van de eigen capaciteit bij bewegen of trainen. Dit vormt de basis voor alle experimenten in dit proefschrift, waar participanten altijd geïnstrueerd werden om op hun eigen tempo te wandelen of (hard) te lopen. Bovendien behandelen we de voornaamste onderzoeksvragen en de belangrijkste concepten binnen het onderzoek naar muziek en bewegingsinteractie. Als laatste wordt er een algemeen methodisch overzicht gegeven van de proefopzet van de studies in dit proefschrift.

Naar aanleiding van de twee voornaamste onderzoeksvragen kan dit proefschrift in twee delen worden opgesplitst. In het eerste deel - Aanpassingen in Beweging-naar-Muziek - bespreken we hoe mensen hun bewegingen aanpassen als ze muziek horen. Dit deel omvat één studie naar het spontane effect van muzikale expressie op de zelfgekozen wandelsnelheid (hoofdstuk 2). In deze studie werden deelnemers (N = 30) gevraagd om twee maal 15 minuten te wandelen, terwijl ze verschillende stukken muziek hoorden die afgewisseld werden met stilte. De enige opdracht was om te wandelen op hun eigen comfortabele tempo zoals ze dat ook zouden doen als ze buiten een korte wandeling zouden maken. Hun gemeten wandeltempo werd als basis gebruikt voor de muziekselectie: bij het starten van elk nieuw nummer moest het muziektempo overeenkomen met het wandeltempo. Elk nummer duurde één minuut en behalve bij de start van het nummer werd het muziektempo verder niet gemanipuleerd. Van elk nummer werd de gemeten wandelsnelheid en de staplengte vergeleken met die in de voorafgaande stilte. De belangrijkste uitkomst van dit experiment was dat muziek met een tweevoudige structuur qua accentuering (elke twee of vier beats) de wandelsnelheid en staplengte deed vergroten, terwijl een drievoudige structuur (accenten op elke derde of zesde beat) deze juist verkleinde.

In tegenstelling tot aanpassingen in Beweging-naar-Muziek gaat het tweede deel van dit proefschrift over het uitlijnen van Muziek-naar-Beweging en hoe dergelijke uitlijningsstrategieën ingezet kunnen worden om menselijke beweging spontaan te manipuleren. Dit deel omvat drie studies. In een eerste studie worden bij (hard)lopen verschillende tempo matchende uitlijningstechnieken getest en vergeleken op het vlak van bewegingsparameters en motivatie (hoofdstuk 3). Deelnemers (N = 36) moesten (hard)lopen waarbij muziek met behulp van zes verschillende uitlijningstechnieken werd afgespeeld. Één van deze zes technieken fungeerde als controleconditie waarin de muziek juist niet in tempo overeenkwam met het looptempo (het gemeten looptempo plus of minus 20 BPM). In twee condities bestaat de uitlijning uit tempo matching: ofwel continu, ofwel slechts aan het begin van een nieuw nummer. In de overige drie condities wordt de uitlijning bepaald door aanpassingen van de relatieve fasehoek, wat erop neerkomt dat het moment van de beat in de muziek zo geplaatst wordt dat het exact overeenkomt met het moment dat de voet de grond raakt. Dit wordt ofwel slechts aan het begin van de conditie gedaan (in-fase start van de muziek, gevolgd door continue tempo matching), of continu per afzonderlijke stap, of volledig continu. Het hoogste niveau van synchronisatie werd bereikt met de twee technieken die de relative fasehoek continu aanpassen. Bovendien resulteerden deze twee condities in lagere looptempi ten opzichte van de andere condities (met lagere synchronisatieniveaus). De resultaten lieten ook zien dat de betreffende afnames in looptempo sterker waren voor vrouwen dan voor mannen. Ten slotte werden er hogere motivatieniveaus waargenomen voor de condities met continue fasehoek aanpassingen in vergelijking met de controle conditie waarbij absoluut geen synchronisatie met het muziektempo plaatsvond.

De tweede studie betreft de spontane entrainment van looptempo met muziektempo (hoofdstuk 4). Recreatieve (hard)lopers (N = 16) werden gevraagd om vier rondes van 200 m, in 11 verschillende tempo condities af te leggen. Tijdens elke eerste ronde liepen de deelnemers op hun eigen tempo, zonder muziek. Het looptempo werd geregistreerd en gedurende de tweede ronde kregen de lopers muziek te horen die in tempo overeenkwam met het gemeten looptempo. In de laatste twee rondes werd het muziektempo stabiel gehouden of lichtjes gemanipuleerd (3.0, 2.5, 2.0, 1.5, of 1.0% hoger of lager dan het gemeten eigen tempo). Het bleek mogelijk om het looptempo van de deelnemers te beïnvloeden door middel van deze onwaarneembare aanpassingen van het muziektempo. Daarnaast liet de studie zien dat het niveau van entrainment daalde naarmate de tempomanipulaties groter werden. Goede entrainment niveaus werden gemeten bij tempo-aanpassingen tot maximaal 2.5%. De resultaten toonden een groter effect op tempo voor vrouwen dan voor mannen.

Een derde studie onderzocht het effect van kleine tijdsverschuivingen van de beat op het (hard)looptempo (hoofdstuk 5). Meer specifiek ging deze studie over het manipuleren van de relatieve fasehoek tussen de momenten van de muzikale beat en het neerkomen van de voet, en hoe dergelijke manipulaties ons looptempo en onze motivatie kunnen beïnvloeden. Zoals in voorgaande studies, werden recreatieve (hard)lopers (N = 26) gevraagd om op hun eigen tempo (hard) te lopen. In totaal liepen ze negen keer vier minuten. Tijdens de eerste minuut van elke conditie werd er nog geen muziek aangeboden. Het looptempo werd gemeten en het gemiddelde looptempo van de laatste 15 sec werd gebruikt om muziek met een overeenkomstig tempo te selecteren. In de daaropvolgende drie minuten probeerden we het looptempo tot 5% te versnellen of te vertragen. Dit werd op drie verschillende manieren gedaan, namelijk door een klein, middelmatig of groot verschil in timing tussen de beat en de voetstap te introduceren. De studie onthulde een significant effect van de verschillende fasehoek strategieën op het looptempo en de loopsnelheid van de deelnemers. Daarnaast toonden de resultaten een interactie effect tussen geslacht en looptempo aanpassing. Vrouwen pasten spontaan hun looptempo aan: hoger tempo bij de +5% doeltempo condities en een lager looptempo bij de -5% condities. Mannen konden daarentegen wel beïnvloed worden om te versnellen, maar ten opzichte van hun reeds vertraagde looptempo in de niet-manipulatieve conditie brachten de -5% doeltempo condities geen verdere tempovertraging. Behalve de effecten op looptempo en loopsnelheid, toonden de resultaten dat lopen met muziek leuker gevonden werd dan lopen met een metronoom, en dat vertragende tempocondities met muziek minder leuk gevonden werden dan de overige condities met muziek.

De vier studies in dit proefschrift maken ieder op hun manier de spontane interactie duidelijk tussen muziek en menselijke (periodieke) beweging zoals (hard)-lopen en wandelen. Verschillende types muziek hebben een verschillend effect op staptempo, staplengte en snelheid. Daarnaast kunnen, mits gestart met een muziektempo overeenkomstig met het looptempo, kleine manipulaties in muziektempo of in timing van de beats het loopgedrag en de motivatie van de lopers beïnvloeden. Dit zijn interessante bevindingen met het oog op het voorkomen en behandelen van gangbare loopgerelateerde blessures. In het laatste hoofdstuk van dit proefschrift (hoofdstuk 6) bespreken we de resultaten van onze studies aan de hand van de op voorhand gestelde onderzoeksvragen. Daarnaast beschrijven we onze bijdrages aan het onderzoeksveld en mogelijke richtingen voor toekomstig onderzoek. We eindigen het hoofdstuk met een samenvatting van de conclusies van dit proefschrift.

English Summary

In the first chapter of this thesis a general introduction to our work on music-based biofeedback for walking and running is presented. We discuss the strong coupling between rhythms of music and movement and how this coupling strength can be applied to help improve and guide our rhythmic movements in everyday life such as in walking and running. We also discuss the importance of people moving at their own individual capacities. This forms the basis for all of the experiments in this thesis, where participants are always instructed to walk or run in their own tempo. Furthermore, we go over the main research questions and the most important concepts of music and movement interaction are described. Finally, a general methodic outline is given for the experimental design of our studies.

According to the two main research questions the work in this thesis can be categorized into two research pillars. In the first pillar - Movement-to-Music adjustments - we discuss how people adjust their movements when they hear music. More specifically, a study on the spontaneous velocity effect of musical expression on self-paced walking is presented (chapter 2). In this study participants (N = 30) were asked to walk two times 15 minutes, while hearing different pieces of music alternated with silence. They were simply asked to walk in their own comfortable tempo as if they were going on a short walk outside. Their measured cadence was used as a basis for the music selection: the tempo was to match the walker's cadence at the start of the song. For the remainder of the one-minute song no manipulation was performed on the music. For each song the measured kinematics like velocity and stride length were compared to the preceding silence. The general conclusion was that songs with a binary emphasis structure (every two or four beats) had an increasing effect on velocity and stride length whereas a ternary structure (emphasis every three or six beats) had a decreasing effect.

In contrast to Movement-to-Music adjustments, the second pillar of this thesis addresses Music-to-Movement alignment strategies and how such strategies can be used to spontaneously manipulate human movement behaviour. We present three studies that deal with music-to-movement alignment. In a first study various music-to-movement alignment techniques are presented with their different impacts on beat-synchronized running and motivation (chapter 3). Participants (N = 36) had to run with six different alignment techniques: five of them were tested and compared to a control condition where the music tempo deliberately was not aligned to the running cadence (registered cadence plus or minus 20 BPM). One strategy involved music tempo manipulations continuously throughout the running exercise and another only at the beginning of a song. The other three strategies in-

volved relative phase angle manipulations. This means that the exact moment of the beat is adjusted in such a way that it precisely matches the moment of a footfall. This is done either at the beginning of the exercise (followed by continuous tempo matching), continuously per discrete step, or continuously. The highest degree of synchronization was achieved with the two strategies that continuously adapt the relative phase angles. In addition, both these strategies elicited decreased cadence rates compared to the strategies facilitating lower degrees of synchronization. The results also revealed that these decreases were more pronounced for female than for male subjects. Finally, higher levels of assessed motivation were uncovered for the continuous phase angle adaptation strategy, compared to the allochronic control strategy, where no synchronization with the music could be achieved.

The second study concerns spontaneous entrainment of running cadence to music tempo (chapter 4). Recreational runners (N = 16) were instructed to run four laps of 200 m, in 11 different tempo adaptation conditions. During each first lap runners ran at their own preferred cadence without musical accompaniment. The running cadence of the first lap was registered, and during the second lap music with a tempo matching the assessed cadence was played. In the final two laps the music tempo was either kept stable or slightly manipulated by increasing or decreasing with 3.0, 2.5, 2.0, 1.5, or 1.0%. These imperceptible changes in music tempo were able to influence runners' cadence. The study also showed that the level of entrainment deteriorated when the tempo manipulations were larger. Up to tempo changes of 2.5% optimal entrainment levels were observed. Results also unveiled a more pronounced tempo effect for women than for men.

In a third study on shifting the musical beat to influence running cadence (chapter 5), we specifically explored if and how relative phase angle manipulations can impact running cadence and motivation. Again, recreational runners (N = 26) were asked to run in their own preferred running cadence. In total they ran nine times for four minutes. The first minute of each 4-min sequence consisted of running without musical accompaniment. Running cadence was measured and the average cadence of the final 15 sec was used to select a musical track with matching tempo. In the following three minutes we tried to increase or decrease the runner's tempo up to 5%. Three different coupling strengths, meaning a small, medium or big timing difference between the beat and the footfall, were tested. The study revealed a significant main effect of the phase angle adjustment strategies on runners' cadence and velocity. Furthermore, a significant gender interaction effect was found for runners' cadence adaptation. Women spontaneously increased or decreased their running tempo with the +5% and -5% target tempo conditions respectively. Men, however, could be sped-up, but not slowed-down more than the decrease in cadence that was already observed when the musical beats were perfectly synchronized with the footfalls. In addition to effects on kinematics, the results showed higher enjoyment levels with music than with metronome, and a decrease in enjoyment with the -5% tempo conditions.

The four studies presented in this thesis show the spontaneous interaction between music and human cyclic movements like running and walking. Different types of music have different effects on cadence, step length and velocity. In ad-

dition, slight manipulations in the musical tempo and the exact timing of the beats can be used to influence running behaviour and the runner's motivation or enjoyment. In light of preventing and treating common running-related injuries, these are interesting findings. In the final chapter of this thesis (chapter 6) we discuss the results of our studies by means of our earlier posed research questions. In addition, we discuss our contributions to the research field and possible tracks for future research. We end the chapter with a summary of the conclusions of this thesis' work.

List of Publications

Publications in international journals

Van Dyck, E., Moens, B., Buhmann, J., Demey, M., Coorevits, E., Dalla Bella, S., & Leman, M. (2015). Spontaneous entrainment of running cadence to music tempo. *Sports Medicine: Open*, *1*(15), 1–14.

Buhmann, J., Desmet, F., Moens, B., Van Dyck, E., & Leman, M. (2016). Spontaneous velocity effect of musical expression on self-paced walking. *PLOS ONE*, *11*(5).

Maes, P.-J., Buhmann, J., & Leman, M. (2016). 3Mo: a model for music-based biofeedback. *Frontiers in Neuroscience*, *10*(548).

Buhmann, J., Moens, B., Van Dyck, E., Dotov, D., & Leman, M. (Submitted). Beat synchronized running and motivation: an investigation of different music-to-movement alignment strategies.

Chapters in international publications

Leman, M., Buhmann, J., & Van Dyck, E. (2017). The empowering effects of being locked into the beat of the music. In C. Wöllner (Eds.), *Body, Sound and Space in Music and Beyond: Multimodal Explorations* (pp. 13-28). London, UK: Routledge. ISBN:9781472485403

Publications in international conferences

Buhmann, J., Moens, B., Lorenzoni, V., & Leman, M. (2017). Shifting the musical beat to influence running cadence. In E. Van Dyck (Eds.), *Proceedings of the 25th Anniversary Conference of the European Society for the Cognitive Sciences of Music (ESCOM)*, Ghent, Belgium.

1

Introduction

1.1 Problem situation

1.1.1 Problem description

The rhythms of movement and music (an external auditory stimulus) are tightly coupled (Maes, Leman, Palmer, and Wanderley, 2013). We experience this when we spontaneously or deliberately move on the beat of music (e.g., in dance), or when we enjoy performing physical and sport activities (e.g., running or cycling) together with music. This drive to match movement to rhythm is natural, develops at a tender age (Honing, Bouwer, and Háden, 2014), and is likely hard-wired in humans, as shown by cognitive sciences and neurosciences (Salimpoor, Zald, Zatorre, Dagher, and McIntosh, 2015; Schaefer and Overy, 2015). The aim of this work is to exploit the link between music and movement in order to boost individual performance, health and wellness. We hereby focussed on improving cyclic movements like walking and running, because these type of exercises bring forth a clear tempo and rhythm in the human movements. Since such qualities reflect typical aspects of music, running and walking are outstanding physical activities to be coupled with music.

Nowadays running is a popular easy accessible activity to stay in shape or even improve one's fitness. In the studies involved in this thesis health and wellness are not registered directly, rather the goal is to optimize musical and technological conditions that enhance people's motivation to go running and be physically active. The studies that involved running (chapters 3 to 5), were always performed with healthy recreational runners. Naturally, not everyone likes or is fit enough to start running (e.g. because of older age or walking disabilities). But being able to influence those people's motivation to walk (more or better) would also be an achievement. Therefore, one study (chapter 2) is devoted to exploring musical aspects that affect walking.

We strongly believe in an individualized approach. This means starting from a person's capacity, or more precisely, starting from each person's own comfort tempo in walking or running. In sections 1.4.1 and 1.4.2 some background is provided on the benefits of exercising at a self-chosen tempo or intensity. In addition, we mean to explore how individual motivation can be optimized. We believe this is done not only by using any kind of music but by selecting music that is tailored to the task (e.g. running) and to someone's personal music preference.

Although the overall goal is to exploit the link between music and movement to improve individual performance and health, the studies in this thesis aim at exploring just how music and music manipulation can impact human movement (walking or running). The results lie at the basis of applying music in the fields of sports and rehabilitation. On the one hand the focus is on finding relationships between certain acoustical (loudness and pitch) and temporal (recurring) elements in music and the use of less or more vigor in human movement. On the other hand we investigate ways of manipulating and aligning music with human movement and how manipulating aligned music can spontaneously impact movement.

1.1.2 Research questions

In this thesis we are concerned with the questions if and how music and technology can be used to affect (i) kinematic parameters for walking and/or running, and (ii) motivation. In order to study these factors several empirical studies were designed and carried out, involving measurements and analyses of sounds (pitch, loudness, beat annotations) and human movements (step frequence or cadence, step size and velocity). In addition qualitative measures were obtained via questionnaires, such as physical enjoyment, motivational level of the music, and ratings of perceived exhaustion. Section 1.3 on Methods offers a general breakdown of the studies executed in the context of this thesis.

The two main research questions are:

- Can expressive features of music influence the velocity of self-paced walking, spontaneously?
- Can we use music-manipulating techniques to spontaneously influence walking/running kinematics and motivation?

The first question relates to how music and expressive musical parameters other then tempo influence our movements. This pillar of the thesis is discussed in chapter 2 and concerns one study on self-paced walking with tempo-matched music. In this study people were asked to walk in their own comfortable tempo while hearing alternating pieces of music and silence. The musical excerpts were selected and slightly adjusted to match in tempo with the measured walking cadence. Different kinematic parameters like cadence, stride length and stride velocity were compared to their reference values while walking in silence. Our hypothesis was that certain songs would have an increasing or activating character reflected in the stride length and walking velocity, and that this could be linked to certain musical features (such as in Leman, Moelants, Varewyck, Styns, van Noorden, and Martens (2013)). We hypothesized that such a link between musical features and walking behaviour could also be found for musical excerpts that had a decreasing or relaxing effect on walking kinematics. The focus in this part of the thesis is on finding specific musical features that can be linked to the use of less or more vigor in our walking movements.

Where the first research question is concerned with how we adjust our movements to different types of music, the second research question concerns the reverse: how can we align music, or rather the musical beats, to our movements, and can we use these type of alignment technologies to spontaneously influence these movements and/or our enjoyment of the running exercise? This pillar of the thesis is described by three studies on running.

The first study in chapter 3 is concerned with comparing different types of music-to-movement alignment strategies (see also Moens, Muller, van Noorden, Franěk, Celie, Boone, Bourgois, and Leman, 2014). How can we maximize synchronization between the moments of the footfall and the timings of the musical beats? How does increased synchronization affect kinematic parameters, such as cadence, step length and step velocity? Does it also affect our motivation? These are the main research questions in this study.

A logical follow-up question was: can we use the positive findings for running in synchrony with the musical beat together with the concept of entrainment to influence runners' cadence and velocity on a spontaneous/subliminal level? Chapter 4 describes a study where the influence of small tempo manipulations in the music on running cadence and velocity was studied. After matching the tempo of the music to the individual running cadence, the tempo of the music was sligtly adjusted (up to a maximum of ± 3%), and changes in the running cadence and velocity were analyzed. Changing the tempo of the music is achieved by stretching or compressing the time signal of the music. In other words, the duration of each inter-beat-interval (IBI) is lengthened or shortened. This method, however, does not take into account the specific moments of the feet touching the ground. Even though the amounts of tempo change are rather small and subliminal, the changes not being relative to the steps will cause the runner having to re-entrain his or her steps after loosing the link with the beat.

Therefore, a similar research question and experimental design is adopted in the study described in chapter 5. This time, after matching the musical tempo to the running cadence, we adapted the musical tempo through shifting each subsequent musical beat in relation to the expected time of the next footfall. This way the link between the beats and the footfalls is kept while changing the musical tempo. Our hypothesis was that playing the beats slightly later than the footfalls would decrease running cadence, while playing the beats just before the footfalls would increase running cadence.

1.1.3 Research domain

This thesis' topic is an interdisciplinary one. It bridges embodied musicology, psychology, kinematics and computer science. Unlike music cognition, where the focus is on the perception of music, musical parameters (e.g. pitch, melody, rhythm) and musical structure, embodied musicology links musical action and perception. When listening to music people not only perceive the music, they actively or passively engage with it. The human body serves as a mediator between external and internal processes, e.g. between a musical stimulus and what happens in the mind. Therefore, what happens in the mind depends on properties of the body and how we move. When we walk or run with music, music influences our kinematics (body) and our motivation (mind), and emotions (mind) in turn affect our performance (body).

Where the musical tempo could be seen as the glue between the bodily movements and an external auditory stimulus, it is the expressivity in music that drives our interaction with music.

1.2 Concepts of music and movement interaction

The way we study human interaction with music is well-founded in the theory of **embodied music cognition** (Leman, 2007; Godøy and Leman, 2010). In music cognition, we assume that sense-giving activities (actions that give meaning to our experiences) are emerging from dynamic interactions with our environment. A complete understanding of such interactions needs both the physical and the experiential level. In embodied music cognition the emphasis is on the physical level: the human body, seen as a mediator for sense-giving activities.

Human interaction with music can be seen as a special form of **human-machine interaction**. Where human-machine interaction concerns the study of how people interact with computers and technology, music-movement interaction concerns the study of human movement when hearing or listing to musical stimuli. As in all forms of interaction mirroring plays a role and hence concepts of sensorimotor mechanisms, like prediction, entrainment, and alignment are important in our studies.

Strictly speaking we talk about **synchronization** when salient moments in someone's movements coincide with salient moments in the music. An example of this is a runner who exactly matches the moments of his footfalls with the moments he perceives the musical beats. A similar, though slightly different example is a runner that puts down his feet exactly between the beats (on the off-beat), or always slightly before the beats. Sometimes these cases are also referred to as being in synchrony with the beat, but it is more correct to refer to them as cases of **phase coherence**. This means that the relationship between the footfalls and the beats is very stable, and that the tempo of the movement is identical to the tempo of the music. Another term to refer to these instances is **phase-locking**: the relative proportion between the beats and the footfalls stays the same. However, when the relationship between beats and footfalls is unstable, the cadence of the runner is no longer the same as the tempo of the music. This is referred to as not being synchronized or moving with phase incoherence.

According to Leman (2016) **entrainment** can be defined as a type of interaction that drives human rhythm to synchronize with a musical rhythm. This drive to synchronize can be explained by attractor dynamics, based on **prediction error minimalization**. If a salient movement marker is out of phase with a salient musical marker, we observe an error (be it consciously or subliminally) and try to compensate for this error by shortening or lengthening the duration up to the next salient movement marker (Moens and Leman, 2015; Repp and Su, 2013; Thaut, McIntosh, and Hoemberg, 2014). The stability between two similar music and movement rhythms is highest when the strongest salient markers in these rhythms exactly match (e.g. the footfalls and the beats are in phase), and somewhat less stable when they are mirrored (in anti-phase).

The process of entrainment can be seen from the viewpoint of the human adapting to an external stimulus. We use the term **alignment** if we look at it from the viewpoint of the music technology, or in other words, when the musical beats are adaptive to the footfalls. Within this thesis we looked at different methods of 'aligning' or matching the musical stimulus to the measured walking or running behaviour of the participant. In this context we speak of alignment strategies, ranging from simply selecting a musical track with the same tempo as the walking or running cadence, to strategies where the beats are continuously matched to the moments of the footfall. Such alignment strategies can be used within **sonification or auditory biofeedback systems** that translate human movement to sound or music. The use of music in auditory biofeedback systems serves three purposes: (i) motivating us to move or move more/longer, (ii) monitoring our movements to increase awareness, and (iii) modifying our movements to e.g. reduce the risk of injury or increase our health or performances (Maes, Buhmann, and Leman, 2016).

All of the above concepts play a roll in this thesis and they will be attended to more in-depth with specific examples where needed.

1.3 Methods

1.3.1 Subjects

All studies that are part of this thesis were approved by the Ethics Committee of the Faculty of Arts and Philosophy of Ghent University and were in accordance with the statements of the Declaration of Helsinki. Participants were informed about the task beforehand and were asked to sign a form in which they declare to participate voluntarily. They could stop the experiment at any time if needed and they agreed that the experimental data would be used for scientific and educational purposes.

For the studies concerning running behaviour we recruted healthy recreational runners between 18 and 50 years old, that were able to run or jog for 30 minutes. The average age of the participants for these three studies ranges from 22 to 31 years. In the study on walking (chapter 2) we had less strict age requirements, since walking is an activity that people usually still do well when they get older. Participants were asked to report being able to comfortably walk for 30 minutes without stopping. The average age in this study is 37 years. Since running is a popular physical activity, there was a lot of interest in participating and we were able to put together groups of participants where the amount of men was more or less equal to the amount of women. For the study on walking, we had less interest and therefore decided to focus more on the size of the group than on having a gender-balanced group.

1.3.2 General procedure

Figure 1.1 shows a schematic overview of the general research design of the studies. Phase A reflects the first part of the condition were the participant walks or runs in silence, and where the average cadence is measured. This part is usually used as a reference for the rest of the condition, where the kinematic measurements are compared against. The measured average cadence value is then used in phase B to either select tempo-matching music or to select and play tempo-matched music. Finally, phase C can be described as the manipulation phase of the experimental condition. In our experiments, different types of manipulation are used. In chapter 2 the manipulation simply comprises a change in musical track: another tempo-matched track is selected. However, in chapter 4 the manipulation consists of a tempo change in the music.

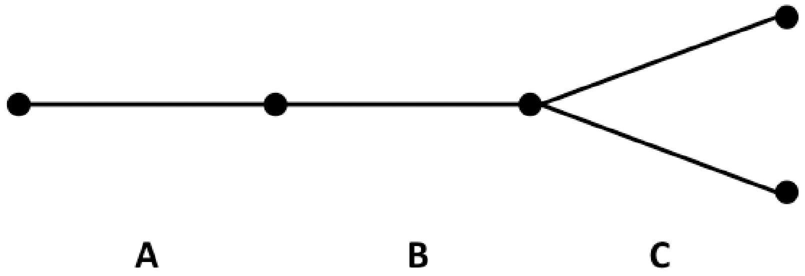


Figure 1.1: Schematic overview of general research design.

1.3.3 Music selection protocol

The use of music while walking or running is at the basis of this thesis. Therefore, for each of the experiments we needed to select music. Since we acknowledge the positive effects of walking or running at one's own comfortable tempo (see section 1.4), this meant selecting music in the range of 80 to 130 BPM for walking and from 130 to 200 BPM for running. This way we could be sure there would be music available for all participants, irrespective of their individual cadence. More specific information on the semi-automatic music selection protocol can be found in appendix A.

Besides the tempo range, we also took into account the stability of the tempo. We only selected musical tracks were the musical tempo, expressed in beats per minute, was stable enough. This was either done by excluding tracks where the difference between maximum and the minimum BPM value within the track was larger than 5 BPM or when the standard deviation of the tempo was larger than 2.

In addition, the beats had to be annotated, meaning that for each beat the exact moment in time within the track needed to be registered. This was done automatically with beat tracking software (Dixon, 2007; Bogdanov et al., 2013), but was always checked and if possible corrected manually afterwards. Having these times annotated was necessary for the musical feature selection that was used in the study on walking, and for the music-to-movement alignment strategies that were used and tested in the three experiments that concerned running.

Finally, in order to motivate participants as much as possible, we used motivational scores for musical tracks used in earlier experiments to select songs with high motivational qualities. We also made sure to select from different genres, spreading tracks from the different genres as evenly as possible across the whole tempo range of the music database. This way there would be music available for everyone's taste, or at least for the majority of the participants.

1.3.4 Equipment and measurements

Gait descriptors

In all the involved studies in this thesis the human movement of interest is running or walking gait. The key points in gait movement are the footfalls or steps. From the spatial and temporal position of these salient markers the main three descriptors for this type of cyclic movement can be derived. First of all, there is **cadence** or **step frequency** that is referred to by the number of steps per minute (SPM). This descriptor is purely based on the temporal aspects of gait movement: when and how often do the feet touch the ground? Second, is the **step or stride length**. This descriptor is derived from the spatial markers of the footfalls: where do the feet touch the ground? The step size is the distance between the position where one foot touches the ground (e.g. the left heel) and where the next foot touches the ground (e.g. the right heel). In the case of stride length, we talk about the distance of a complete gait cycle: from left to left foot, or from right to right foot. Finally, a third gait descriptor of interest is the **velocity**. It is derived from both temporal and spatial markers of the movement.

These gait descriptors are either measured with professional hard- and software like OPAL-sensors in conjunction with MobilityLab$^{\text{TM}}$ software (Mancini, King, Salarian, Holstrom, McNames, and Horak, 2012), or with DJogger-based hard- and software that was developed within our lab (Moens, Muller, van Noorden, Franěk, Celie, Boone, Bourgois, and Leman, 2014). In the latter case, we only measure the temporal positions of the footfalls, but we lack the spatial information. Combining DJogger with a sonar (see Figure 1.2) that detects poles that were equidistantly placed around the running track, made it possible to measure the velocity of the runner, which in turn enabled us to calculate the length of the steps.

Music and gait: relative time descriptors

Like walking or running gait, most popular music also contains key points that mark temporal positions, namely the beats. Therefore rhythms and musical tempi should be designed or selected effectively and tailored to the individual's walking or running cadence.

If we want to measure synchronization of movement with music, we need to measure the exact moments in time of the salient markers in movement and music: the footfalls and the beats. Like 'time of day' or 'day in a week' both of these salient markers can be considered as temporal periodic data: events that reoccur over time. This type of data does not have a true 0, and values can be converted to an angular measurement. Since 0º and 360º are in fact the same angles, a special type of statistics is needed to calculate e.g. the mean angle: directional (or circular) statistics (Berens, 2009).

Figure 1.2: The equipment mounted on the backback consisting of (A) a sonar distance sensor, (B) headphones, (C) 7" tablet, (D) Wi-Fi router, and attached to the ankles (E) iPods.

Relative phase angle For each beat a relative phase angle can be calculated, that indicates the position in time of the footfall relative to the beat. Each inter-beat interval (IBI) is considered as a complete cycle: 360º. A relative phase angle of 0º refers to a footfall that is exactly timed on the beat, and an angle of 180º refers to a footfall that is timed precisely in between two beats (the off-beat position). Such a relative phase angle ϕ can be calculated for each step and the IBI the step fell within. In Eq. (1.1) S_t refers to a step at time t. B_1 is the time of the beat that occurred before S_t and B_2 is the time of the first beat after S_t.

$$\phi = 360 * \frac{S_t - B_1}{B_2 - B_1} \tag{1.1}$$

Resultant vector length Although the average relative phase angle tells us when a runner on average put his or her feet down (before, after or on the beat), it does not tell us anything about the stability of the relative timing between beat and footfall. A way to measure this is by looking at the resultant vector length or the mean phase coherence (Mormann, Lehnertz, David, and Elger, 2000), as shown in Eq. (1.2), where N is the number of samples and ϕ is the relative phase angle for step S_t. This is a crucial quantity for the measurement of circular spread in directional statistics. The values can range from 0 to 1. $|R|$ reaches the value 1 in case of strict phase locking, whereas $|R| = 0$ when phase angles are randomly spread over time, i.e. a uniform distribution of phase angles.

$$|R| = \left| \frac{1}{N} \sum_{S_t=0}^{N-1} e^{i\phi_{S_t}} \right| = 1 - CV \tag{1.2}$$

Degrees of synchronization

When we talk about synchronization we consider different degrees or stages of synchronization. The paragraphs below describe these degrees of synchronization and figure 1.3 visualizes them in terms of relative phase angles and resultant vector lenghts: (a) no synchronization, (b) entrainment, (c) phase locking, (d) perfect synchronization = phase locking at 0º.

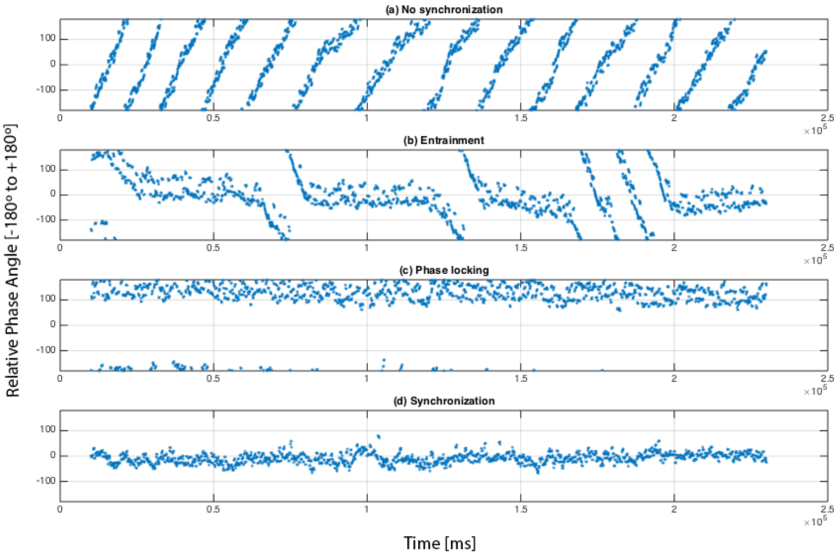


Figure 1.3: Degrees of synchronization.

No synchronization If the human movement tempo is completely different from the musical tempo, no synchronization is achieved. Perhaps synchronization (a 0º relative phase angle) can be observed at some moments, but these specific moments occur merely by chance. Figure 1.3-a shows the corresponding distribution of relative phase angles in a polar plot. The figure shows a uniform distribution of the phase angles and a small resultant vector length, indicating a lack of phase coherence.

Entrainment The process of entrainment can be triggered if the tempo of the music is close enough to the tempo of the human movement. The musical beats affect the running in such a way that the cadence will change towards the tempo of the music, and the timing of the footfalls will gradually adjust to the timing of the beats (0º), the off-beats (180º) or another stable proportion of the rhythm. Figure 1.3-b shows this process of entrainment several times: going from a state of no synchronization (a non-horizontal line) to a state of phase coherence (a horizontal line).

Phase locking When we speak about phase locking we talk about a special form of synchronization. The tempo of the human movement perfectly matches the tempo of the music. The salient movement moments (footfalls) might differ in time from salient musical markers (beats), but always in the same relative proportion, e.g. a footfall on the off-beat, at 180º relative to the moments of the musical beats. As long as the relation between beats and footfalls is stable, we talk about phase locking. Figure 1.3-c shows an example where the phase is locked at approximately 150º. A special form of phase locking is a stable phase angle at 0º, or in other words perfect synchronization (see Figure 1.3-d).

Qualitative data

Besides the quantitative kinematic and musical measurements, we also gathered qualitative data through several questionnaires. In all studies, we asked people to rate their perceived amount of exertion (RPE) indicated on the Borg Scale (Borg, 1998). Participants were also requested to rate the motivational aspects of the musical tracks they heard while running with the Brunel Music Rating Inventory-2 (BMRI 2) developed by Karageorghis, Priest, Terry, Chatzisarantis, and Lane (2006). Furthermore, in some of the studies (chapters 3 and 5) participants had to indicate their physical enjoyment. This was done on the 8 item version of the Physical Activity Enjoyment Scale (PACES) (Kendzierski and DeCarlo, 1991; Mullen, Olson, Phillips, Szabo, Wójcicki, Mailey, Gothe, Fanning, Kramer, and McAuley, 2011), a single factor scale to assess the level of enjoyment during physical activity in adults across exercise modalities. Finally, participants were always asked to fill out a questionnaire on personal background, music education and sports training.

1.3.5 Manipulation techniques

Nowadays techniques exist to slow down or speed up music, without perceivably affecting the tone or pitch of the music. Such a technique can be used in a music-to-movement alignment strategy that continuously manipulates the musical tempo by changing the duration between subsequent beats. It does not, however, take into account the specific moments when the beats occur, or how these time instants relate to the instants of the footfalls. In other words, the relative phase angle between beat and step is disregarded. An alignment strategy that is able to consider relative phase angles might be better suited to keep the synchronization level high and to spontaneously manipulate runner's cadence.

Tempo adaptation

To understand what a change in tempo implies, one can consider time as an elastic band. If we stretch time, the elastic band gets longer and the distance between salient markers such as the beats increases. As it takes longer before the next beat is played this means the tempo of the music slows down. We achieve the opposite by releasing the rubber band: the time dimension shrinks and beats are played closer together, resulting in a speed up of the music. In chapter 4 a study is described that tests different music tempo adaptation rates and their influence on running cadence. The study reveals that music tempo is capable to influence running tempo, at least if the tempo difference is within approximately 2,5%.

Relative phase angle manipulation

Rather than stretching or compressing the dimension of time, we can also shift it. Simply shifting the time dimension once, will not influence the musical tempo. However, if such a shift is induced at a series of steps, each shifted beat will influence the next footfall, which will result in a tempo change. This technique builds on the concept of entrainment where salient musical markers attract salient movement markers. The idea is that if a beat is played before the moment of the footfall, the runner will (consciously or unconsciously) try to revert to a 0° relative phase angle by speeding up. On the contrary, if a beat is played after the moment of the footfall the runner will perceive this (subliminally or consciously) as being too fast and will try to slow down to get back into perfect synchrony with the music. Chapter 5 describes a study in which such relative phase angle manipulation techniques were tested.

1.3.6 Statistical analysis

In each study the analysis process started with inspecting the data with graphs (scatter plots, histograms, box-plots, etc.). Outliers were checked and if needed corrected or excluded from analysis. In addition, assumptions of normality (Kolmogorov–Smirnov test) and homogeneity of variance (Levene's test) were checked. Depending on the outcomes and on the number of comparisons to be made, a fitting test was chozen for the statistical analysis of the data. In case the data were distributed normally, parametric tests, such as a t-test or (Repeated Measures) ANOVA were performed. If the data turned out to be non-normally distributed, non-parametric tests, such as Friedman's ANOVA or Wilcoxon signed-rank tests were used. Either one of these tests, resulted in accepting or rejecting the respective null-hypothesis. In each study, the p-values (significance) and effect sizes were reported.

1.4 Why an individualized approach matters

Since one of our goals was to boost individual performance, health and wellness, we needed to come up with methods that optimize music selection and music technology to fit individual parameters. These parameters not only concern kinematic constraints (e.g. preferred cadence), but also individual musical preference. In the following paragraphs we explain the benefits of exercising at your own comfortable tempo and intensity, why music alignment technologies need to take this into account, and how being able to select from preferred music can benefit individual performance.

1.4.1 Self-paced walking or running

An important aspect in all the involved studies is the fact that people were always encouraged to move in their own tempo. Even for the studies were we tried to influence runners' cadence we always started from the basis of self-paced running. There are multiple studies that underline the benefits of self-paced walking or exercise over moving at a prescribed tempo or intensity. Williams (2008) states that self-paced exercise elicits more positive affective responses than prescribed intensity training, which leads to increased adherence to exercise programs. He pleads for a shift in physical activity guidelines emphasizing performance or exercise at an intensity that feels good rather than at a specific prescribed intensity. This could benefit training experience and health outcomes.

Similar findings have been reported in the field of gait rehabilitation. A review by Nombela et al. (2013) on rhythmic auditory stimulation (RAS) for patients with Parkinson's disease (PD) concludes that rhythms seem to lose therapeutic value when they are not tuned to the individual's pace, or when they become cognitively demanding. Every individual PD patient has specific clinical indications and responds differently to outer stimuli. Therefore, neurological music therapies for PD patients should become more and more custom-made. In another study by Roerdink et al. (2011) the examination of different metronome rates in gait rehabilitation revealed superior auditory-motor coordination for step frequencies near an individual's preferred cadence. This suggests that the further away step frequencies become from a patient's preferred cadence, the less effective acoustic rhythms will be in influencing gait.

1.4.2 The v-f relation

Gait can be described by three parameters: velocity (v), step frequency (f), and step length (d). Those three descriptors are closely linked. Velocity is the result of step frequency and step length and changes in step length and/or step frequency can impact velocity. This is referred to as the v-f relation. According to Kuo (2001) a person's preferred v-f relation is based on minimizing an O_2 consumption cost, and Bertram and Ruina (2001) concluded that depending on which kinematic parameter is constrained this results in different v-f relations. Besides the fact that this v-f relation seems to be dependent on the individual and on constrainment factors, the variability in step size or stride length seems to increase when instructed to walk at a frequency of 130 SPM or higher (Styns, van Noorden, Moelants, and Leman, 2007) or when deviating too much from an optimal preferred cadence of on average 120 SPM (Danion, Varraine, Bonnard, and Pailhous, 2003). All these influences on v-f relation tell us that imposing a certain step frequency should be done with great care, especially if the frequency deviates quite a bit from a participant's preferred cadence. Therefore, in the studies presented in this thesis participants were always asked to walk or run in their own preferred tempo, after which their registered cadence was used as a basis for selecting tempo-matching music.

1.4.3 Music and motivation

The basis of RAS lies in providing auditory stimuli with a certain tempo: usually an individual's comfort tempo or a slight deviation from it. This is typically done by using metronome stimuli with respective tempi. However, music seems to be a more motivational type of stimulus to be used in RAS. Although there is plenty of music out there, we do not advocate to use just any type of music, but rather to use music that is both adequate for the task (e.g. running) and preferred by the user. A factor of importance is the type of music: depending on certain expressive musical qualities, music can increase or decrease walking performance over walking with a metronome stimulus as a result of increased or decreased step length (Leman et al., 2013). Furthermore, personal musical preference has been shown to play a role. A study by Nakamura, Pereira, Papini, Nakamura, and Kokubun (2010) revealed higher RPE for cycling while listening to non-preferred music, compared to listening to preferred music or no music. In addition, participants' performance was greater with preferred music (longer distance) than with non-preferred music. Another study by Cole and Maeda (2015) showed that compared to listening to non-preferred music, listening to preferred music has a positive effect on running performance (endurance) for women.

In the music selection process for our experiments we focussed on selecting different types of music from a broad range of tempi, to make sure that the music database contained a sufficient number of songs for everyone's taste and tempo.

1.5 Outline

Figure 1.4 gives a schematic overview of the work presented in this thesis. The current chapter describes the theoretical framework for the studies that were performed within the thesis. In accordance with the two main research questions (see section 1.1.2), the work can be devided into two different research pillars. First, we look into the topic of **movement-to-music adjustments**. This thesis contains one study related to this topic, discussed in chapter 2. It describes how expressivity in different types of music can influence our movements, more specifically our step length while walking. The second research pillar considers the topic of **music-to-movement alignment**. The topic is covered by three studies in which different techniques are tested that manipulate the musical signal to more or less mirror the tempo and moments of the footfalls of people's running gait. Chapter 3 includes a study that explores music-to-movement alignment techniques that align the music with the movement with several degrees of synchronization. Chapters 4 and 5 cover different manipulation techniques. In chapter 4 a music-to-movement alignment technique is used (i) to match music tempo to a runner's cadence, and (ii) to slightly deviate the music tempo from the measured comfort tempo of the runner. The study in chapter 5 is similar, but takes into account the exact moments of the footfall. We explored if shifting the beat just before or after the footfall could increase or decrease e.g. running cadence. The final chapter (chapter 6) summarizes what we have learned and achieved in relation to our research questions, and how this work could contribute to, or serve as a starting point for future studies.

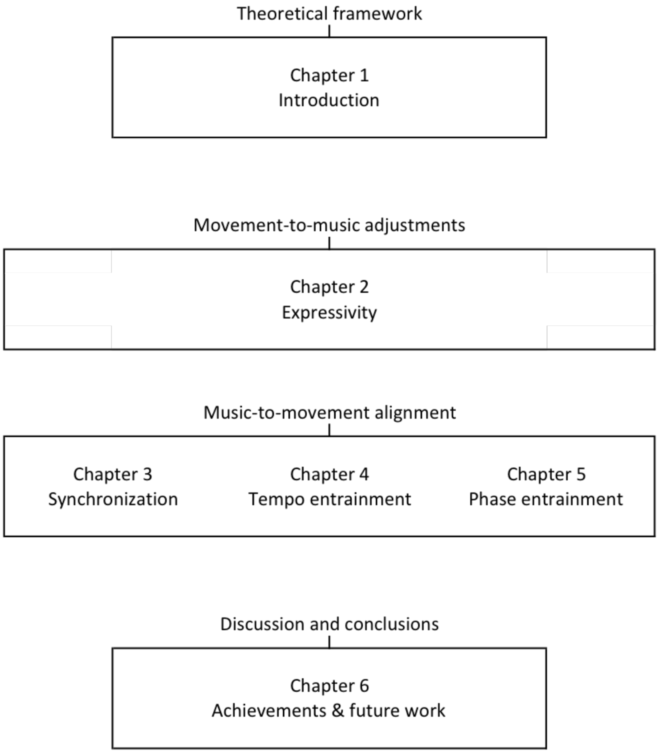


Figure 1.4: Thesis overview.

My main contribution is: co-development of experimental design, execution of experiment, main analysis of the data, and writing the paper.

2

Spontaneous Velocity Effect of Musical Expression on Self-paced Walking

Buhmann, J., F. Desmet, B. Moens, E. Van Dyck, and M. Leman

In *PLOS ONE*, 2016, *11*(5)

Abstract

The expressive features of music can influence the velocity of walking. So far, studies used instructed (and intended) synchronization. But is this velocity effect still present with non-instructed (spontaneous) synchronization? To figure that out, participants were instructed to walk in their own comfort tempo on an indoor track, first in silence and then with tempo-matched music. We compared velocities of silence and music conditions. The results show that some music has an activating influence, increasing velocity and motivation, while other music has a relaxing influence, decreasing velocity and motivation. The influence of musical expression on the velocity of self-paced walking can be predicted with a regression model using only three sonic features explaining 56% of the variance. Phase-coherence *between footfall and beat did not contribute to the velocity effect, due to its implied fixed pacing. The findings suggest that the velocity effect depends on vigor entrainment that influences both stride length and pacing. Our findings are relevant for preventing injuries, for gait improvement in walking rehabilitation, and for improving performance in sports activities.*

2.1 Introduction

Studies based on instructed (and intended) synchronization of human locomotion with music show that the expressive features of music can influence the locomotion. Overall, positive outcomes of instructed synchronization with music over no music have been reported. Measurements were related to psychophysical outcomes, physiological outcomes, and kinematic outcomes:

- *Psychophysical outcomes:* Positive results have been found for elite triathletes running on a treadmill while listening to synchronous music (Terry, Karageorghis, Saha, and D'Auria, 2012). Time-to-exhaustion (TTE) increased by over a minute for both running to motivational and neutral music, compared to the no-music condition. These increases respectively represent an 18.1% and 19.7% improvement in performance. Effects on perceived exertion were small in this maximum intensity test. However, a study by Bood, Nijssen, van der Kamp, and Roerdink (2013) on sub-maximal intensities, did find significant effects on ratings of perceived exertion (RPE).

- *Physiological outcomes:* Oxygen consumption is reported to be lower for athletes running with music compared to running without acoustic stimuli (Terry et al., 2012). The use of music is therefore associated with better running economy. Hoffmann, Torregrosa, and Bardy (2012) mention a decrease in energy consumption to be a result of locomotor-respiratory coupling. When instructed to synchronize cycling to a metronome at the participants' preferred cycling tempo the coupling increased, and as a result energy consumption decreased. Another effect on physiology was found in the heart rate. The use of music during treadmill running resulted in higher heart rates, specifically at (near-) maximal perceived exertion (Bood et al., 2013). This suggests, that music helps runners to work at a higher intensity.

- *Kinematic outcomes:* Beat synchronized walking or running has been studied in terms of the kinematic parameters velocity, stride length, and cadence (Styns, van Noorden, Moelants, and Leman, 2007; Leman, Moelants, Varewyck, Styns, van Noorden, and Martens, 2013). If people walked in synchrony with a musical beat, a difference in walking velocity could only be realized through differences in stride length. The stride length being the result of the amount of vigor put into the leg movement, i.e. the embodiment of expressive patterns in the music. Styns et al. (2007) examined the effect of music (over metronome) on step length, on a range of different tempi. The study revealed a resonance effect in the walking cadence at approximately 130 beats per minute (BPM) (van Noorden and Moelants, 1999; MacDougall and Moore, 2005). Based on that result, Leman et al. (2013) instructed participants to synchronize their walking pace to musical excerpts

> with different expression, all at a tempo of 130 BPM. The study showed that some music had activating qualities, increasing the walking velocity, while other music had relaxing qualities, decreasing the velocity compared to the velocity of walking to a metronome.

In this paper, we focus on the effect of tempo-matched expressive music on the velocity and motivation of non-instructed self-paced walking. We call this: the velocity effect. Our research question is twofold.

First, can expressive features of music influence the velocity of self-paced walking, spontaneously? Instructed synchronization implies that humans are asked to adapt to the musical rhythm, irrespective of their preferred (comfort) tempo. However, this imposes a task that can influence the overall velocity effect. In ecological situations we want to work with self-paced walking. Several studies indeed show that self-paced activity is beneficial for motivation and adherence (Williams, 2008; Roerdink, Bank, Peper, and Beek, 2011; Nombela, Hughes, Owen, and Grahn, 2013).

Second, is the velocity of self-paced walking influenced by phase-coherence? Tempo-matched music implies that once the music starts playing, the tempo (and phase) of the music remains fixed. Under this condition, however, it may happen that the human subject entrains to the beat and establishes a stable timing interval between footfall and beat (Moens, Muller, van Noorden, Franěk, Celie, Boone, Bourgois, and Leman, 2014). When that situation happens, we call it phase-coherence, which means that the pace is fixed. Given the fact that velocity depends on both stride length and pace, the question is whether phase-coherence (where pace is fixed) contributes to the velocity effect.

Based on Leman et al. (2013) we assume that some music will have an activating influence while other music will have a relaxing influence. These influences will be reflected in the walking velocity. We also assume that this velocity effect can be predicted using acoustical features that capture the musical expressions. Furthermore, we hypothesize that phase-coherence may diminish the velocity effect, because the pace is fixed and therefore the velocity only depends on stride length. When phase-coherence does not occur, velocity may depend on both stride length and pace effects, giving more freedom to adapt the velocity.

To go one step further towards an individualized approach, this study also explores the relation between motivational ratings and kinematic outcome. We hypothesize that when music results in an increased velocity, music will be experienced as more motivational. When music results in a decreased velocity, music will be experienced as less motivational.

2.2 Materials and methods

2.2.1 Ethics statement

Participants were informed in advance about the task, the procedure and the technology used for measurement. They had the opportunity to ask questions and were informed that they could finish the experiment at any time. They agreed that recorded movement data would be used for scientific and educational purposes only. In agreement with the general standards at our university and our faculty, security was guaranteed (our indoor task is not dangerous), and privacy is respected. Participants did not have to provide informed consent to participate in this study, because this study only involved behavioral knowledge (cf. 7 May 2004 Belgian Law concerning experiments on the human person (Ch.II, Art.2, Par.11)) and the data were analyzed anonymously. This study as well as the consent procedure was approved by the ethics committee of the Faculty of Arts and Philosophy of Ghent University.

2.2.2 Participants

The present study included 30 participants (nine male), with an average age of 36.57 years (*SD* = 14.94), ranging from 17 to 77 years old. Average body weight and body length were respectively 67.80 kg (*SD* = 10.10) and 1.70 m (*SD* = 0.08). All participants were physically healthy, 66.67% had some sort of musical education and 33.33% reported using music while walking or jogging. After the experiment all participants received a CD-voucher as a reward.

2.2.3 Experimental procedure

The experiment took place on a professional 200 m indoor running track in the Flanders Sports Arena of Ghent. Upon arrival, participants were briefly informed about the procedure, after which they were equipped with gait detection sensors and headphones. Participants had to walk 30 min and were instructed to walk as if they were going on a 30 min walk outside. They were not asked to synchronize to the music that would be played to them. To prevent fatigue influencing the results, the 30 min walk was split-up in two blocks of 15 min. This was confirmed afterwards by comparing the first and second part of each block: no significant differences were revealed for stride length with a Friedman's ANOVA, $\chi^2 = 2.50$, $p = .48$. Furthermore, a repeated measures ANOVA showed no significant differences for stride velocity, $F(3,87) = 0.40$, $p = .75$. During the pause (approximately 15 min), participants could have some water and fruit. Each walking block started with a one-minute warm-up, in which no music was played to the participant. In the following 14 min, a sequence of 15 s of silence and one minute of music was played to the participant. A 15 s period of silence was inserted between songs to reset the walking behavior from the preceding music stimulus. The use of this 15 s silence to prevent a memory effect was checked post hoc by comparing the normalized stride length of four groups of data: relaxing songs preceded by relaxing songs (RR), activating songs preceded by relaxing songs (RA), activating songs preceded by activating songs (AA), and relaxing songs that were preceded by activating songs (AR). A repeated measures ANOVA revealed a significant main effect, $F(3, 75) = 8.35$, $p < .001$. Bonferroni post hoc tests were used to follow up this finding. Significant differences were found between activating and relaxing songs, regardless of the preceding music type: RR ($M = 100.01\%$, $SE = 0.13$) vs. RA ($M = 100.51\%$, $SE = 0.13$), $p = .03$; RR vs. AA ($M = 100.62\%$, $SE = 0.11$), $p = .002$; RA vs. AR ($M = 100.10\%$, $SE = 0.12$), $p = .02$; AA vs. AR, $p = .01$. However, RA was not significantly different from AA, $p = 1.00$. Likewise, we did not find significant differences between RR and AR, $p = 1.00$. These results confirm that the preceding song has no memory effect on the stride length during the current song.

During each 15 s of silence DJogger (Moens et al., 2014) measured the walking cadence of the participant. DJogger then selected a one-minute song with a BPM value within a 5% range of the walking cadence, and adjusted the tempo of that song to exactly match the measured walking cadence, after which the tempo of the music was fixed for the duration of the song. This implicated a song-duration of less than a minute when the tempo was increased, and a song-duration of more than a minute when the tempo was decreased. Depending on the total length of the played songs a participant heard 11 or 12 songs within each 15 min block of walking.

After the experiment, participants were asked to rate the music they had just heard. More precisely, they were asked to indicate how motivating the songs were in the walking exercise. The Brunel Music Rating Inventory-2 (BMRI-2) (see Karageorghis, Priest, Terry, Chatzisarantis, and Lane, 2006) was used for rating the music. The test was performed in the sports hall on a laptop with headphones. Normally, a BMRI-2 test is used as a pre-test to select a participant's most motivating songs. This would, however, have had a severe impact on the time necessary to create the music database and the time needed for the BMRI-2 test itself. Instead, we assessed the motivational characteristics of the songs afterwards, which meant maximally 24 songs were evaluated per participant. Finally the participants filled out a questionnaire on personal, musical and sports background.

2.2.4 Stimuli

Participants were instructed to walk in their own comfort tempo, which is the tempo that participants prefer. Since walking cadence generally varies from 90 to

140 steps per minute (SPM), our music database needed to cover all these tempi. We also took into account that i) the database needed to be large enough for each participant to hear different pieces of music and ii) small enough for multiple participants to hear the same pieces of music as often as possible. All participants had to listen to 22-24 songs and therefore each range of 10 BPM in the database was filled with approximately 22 songs. The music was selected from a large labeled music database using the BPM values and mood labels. The selected songs could have different rhythms, but in the selection process we made sure that the songs had clearly audible rhythms, simple enough to walk on. As a result, almost all selected songs had a 4/4 meter. Earlier research by Leman et al. (2013) has shown that some semantic adjectives describing the music are good indicators of activating or relaxing music. The most activating songs were generally labeled as “aggressive” or “loud”, whereas the most relaxing songs were mainly labeled as “tender” or “soft”. In the current study we examined walking behavior on both activating and relaxing music. Therefore, for a pre-selection of songs for our database, we used mood labels that we believed were close to those of Leman et al. (2013), like “rebellious”, “energetic” (activating) and “peaceful”, “melancholy” (relaxing). In total 250 songs were pre-selected and then further processed. The perceived loudness of all songs was normalized and one-minute samples were selected from the songs. In LogicProX the beginning and the end of each sample were edited with a linear 50 ms fade-in and a linear 100 ms fade-out. Beat timing information was extracted using BeatRoot (Dixon, 2007) and finally the consistency of the tempo throughout the songs was checked with MATLAB. Song tempi were considered to be consistent if the tempo variance was within a range of five BPM. After the music preparation process, 84 of the 250 songs were kept, uniformly spread over the database with respect to their activating or relaxing character. Since the sequence of songs played to each participant depended on the walking cadence of each participant, the set-up of the database ensured the selected sequence of songs to be balanced. Furthermore, the DJogger software selected songs randomly within a 5% tempo difference from the participant’s walking tempo, providing a randomized selection of songs as well.

2.2.5 Apparatus

Participants were equipped with a number of sensors and wireless headphones. Two OPAL-sensors were strapped around the lower legs of each participant, above the ankle, facing front. A third OPAL-sensor was strapped around the waist of each participant. Gait data collected with these OPAL sensors was used for analysis. This was done in conjunction with MobilityLab$^{\text{TM}}$ software (Mancini, King, Salarian, Holstrom, McNames, and Horak, 2012). Additionally, two iPods were strapped around the lower legs, just above the ankle, facing outward. The iPods communicated wirelessly with the DJogger software (Moens et al., 2014). The tempo of the song was manipulated once by DJogger, in order to adapt the selected song to the exact tempo of the walking. This adaptation was done before the start of the song, and the tempo was then kept stable for the complete duration of the song. DJogger normally assures that the song starts in-phase with the walking so that the participant hears the beat at the moment of a footfall. Unfortunately, during our experiment the wireless connection was not always stable and not all songs started in-phase with the walking. To compensate for this, the first 10 seconds of all trials were disregarded in the data analysis so that phase-entrained, if it occurred, could have happened. A headphone receiver was strapped around the upper arm and headphones were placed on the head. All equipment - computers, a dedicated receiver, an Ethernet router, an Arduino link between DJogger and MobilityLab$^{\text{TM}}$, and a wireless headphones transmitter - was set up next to the walking track.

2.2.6 Data-analysis

The data for further analysis in this study was derived from the output of the OPAL sensors. MobilityLab$^{\text{TM}}$ software uses the recorded data from the accelerometers within the sensors to calculate the stride length and stride velocity for each gait cycle (two steps) (Mancini et al., 2012). Because MobilityLab$^{\text{TM}}$ and DJogger were synchronized via Arduino, the average stride length and velocity could be calculated for each song and each 15 s silence. The averaged kinematic data for the songs was analyzed statistically with SPSS 22.

2.2.7 Normalized and averaged walking data

A participant's walking behavior depends on his or her body length and weight. Therefore normalized values were calculated for stride length and velocity. For each participant p the average stride length and velocity of a song were divided by the average stride length and velocity respectively of its preceding silence. The silences were assumed to be neutral in terms of activation and relaxation. Thus, the normalized values on each preceding silence equaled 100%. If a song had smaller values (e.g. a slower velocity) than its preceding silence, the normalized value was below 100%. In a final step, the mean normalized stride length and velocity were calculated by averaging the normalized values for song x over all participants that actually walked to song x.

2.2.8 Phase coherent walking

In addition to the normalized kinematic data we analyzed differences in beat-step synchrony. Because this is temporal periodic data, directional statistics (Berens,

2009) were used to compare the beat and step positions in time. A relative phase angle ϕ was calculated for each step and the inter-beat-interval (IBI) the step fell within. In Eq. (2.1) S_t refers to a step at time t. B_1 is the time of the beat that occurred before S_t and B_2 is the time of the first beat after S_t.

$$\phi = 360 * \frac{S_t - B_1}{B_2 - B_1} \tag{2.1}$$

If the phase angle stayed stable over time this is referred to as phase coherence (Mormann, Lehnertz, David, and Elger, 2000). Rather than being interested in strict synchronization with the beat ($\phi \approx 0$), the focus was on a stable phase at any angle. A way to measure this is by looking at the resultant vector length or the mean phase coherence, as shown in Eq. (2.2), where N is the number of samples and ϕ is the relative phase angle for step S_t. This is a crucial quantity for the measurement of circular spread in directional statistics. The values can range from 0 to 1. $|R|$ reaches the value 1 in case of strict phase locking, whereas $|R| = 0$ when phase angles are randomly spread over time, i.e. a uniform distribution of phases.

$$|R| = \left| \frac{1}{N} \sum_{S_t=0}^{N-1} e^{i\phi_{S_t}} \right| = 1 - CV \tag{2.2}$$

Fig. 2.1 shows a histogram of all the resultant vector length values. The distribution of these values clearly shows the presence of two overlapping processes: the process of phase incoherent walking and the process of phase coherent walking. The phase incoherent data can be described with a normal distribution ($\mu = 0.40$, $\sigma = 0.20$). The phase coherent data resembles an extreme value distribution.

Given a normal distribution with mean μ_n and standard deviation σ_n

$$f(x, \mu_n, \sigma_n) = \frac{1}{\sqrt{2\pi\sigma_n^2}} e^{-\frac{(x-\mu_n)^2}{2\sigma_n^2}} \tag{2.3}$$

and an extreme value distribution with mean μ_e and standard deviation σ_e , with $x > 0$:

$$F(x; \mu_e, \sigma_e) = \frac{1}{\sigma_e} e^{(\frac{x-\mu_e}{\sigma_e})} e^{-e^{(\frac{x-\mu_e}{\sigma_e})}} \tag{2.4}$$

then the intersection of both distributions is defined as:

$$\frac{1}{\sqrt{2\pi\sigma_n^2}} e^{-\frac{(x-\mu_n)^2}{2\sigma_n^2}} = \frac{1}{\sigma_e} e^{(\frac{x-\mu_e}{\sigma_e})} e^{-e^{(\frac{x-\mu_e}{\sigma_e})}} \tag{2.5}$$

or

$$\frac{1}{\sqrt{2\pi\sigma_n^2}} e^{-\frac{(x-\mu_n)^2}{2\sigma_n^2}} - \frac{1}{\sigma_e} e^{(\frac{x-\mu_e}{\sigma_e})} e^{-e^{(\frac{x-\mu_e}{\sigma_e})}} = 0 \tag{2.6}$$

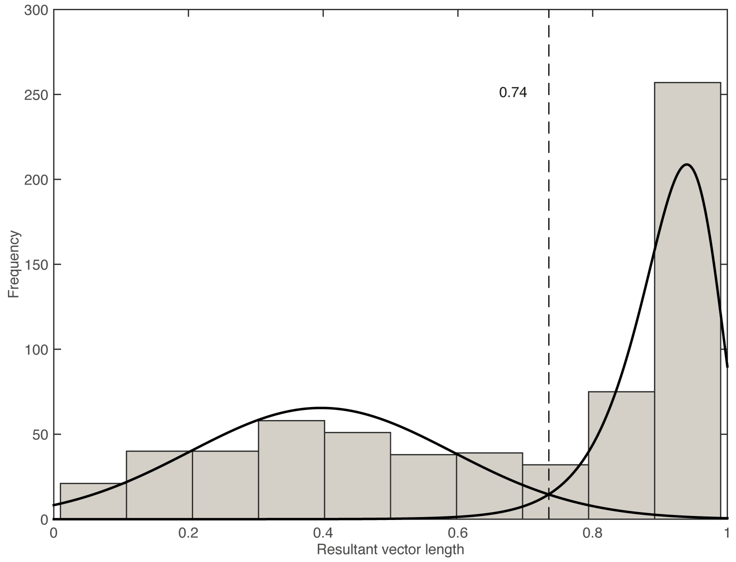


Figure 2.1: Distribution of resultant vector lengths. This histogram shows $|R|$ of all 651 trials, where participants walked to a song, revealing two overlapping processes: phase incoherent walking (low $|R|$ values), which is normally distributed, and phase coherent walking, which has an extreme value distribution. The functions estimating those distributions intersect at a value of 0.74.

Using an iterative process this equation can be approached. As a result, the intersection of both functions was found at $|R| = 0.74$. A split in the data at 0.74 resulted in 300 phase incoherent and 351 phase coherent trials. On top of the histogram, Fig. 2.1 shows where the two functions intersect.

2.2.9 Data partitioning of songs

In order to compare the most relaxing songs to a group of neutral and activating songs, the data set needed to be divided in three groups. The predicted stride lengths (see section 2.3.2) for 59 songs were normally distributed. Instead of simply comparing the normalized stride lengths from the ten most activating songs to the ten most relaxing songs and ten songs from the middle of the distribution, we wanted to partition the normal distribution in a statistically sound way. In other words, the aim was to find the threshold limit values (TLV's) dividing the data in three groups that have an optimal unambiguous character. According to the three-sigma rule of thumb (Grafarend, 2006) nearly all values of a normal distribution lie within three standard deviations of the mean. In order to keep a sufficient amount of data in all three groups of the distribution, the optimum TLV will be around one standard deviation of the mean, at which approximately 68% of the data will be in the middle - neutral - part of the distribution, and approximately 16% of the data will be considered as the activating group of songs and, equally, 16% of the data as the relaxing group of songs. In total, three multiplication factors of the standard deviation were tested: $m = 0.8, 1.0, 1.1$. For each multiplication factor, three groups of data were derived by using the mean minus $m \cdot \sigma$ and the mean plus $m \cdot \sigma$ as boundaries between the three groups. The middle group contained more songs than the group of relaxing or activating songs; therefore a random selection of approximately the same amount of songs was taken from the middle group. A different random selection was taken 10 times and each time an ANOVA was performed between the actual normalized stride lengths for the three groups of music. The mean and standard deviation were calculated from the p-values of the 10 trials. The TLV's were well chosen once the mean p-value was small and stable enough. Table 2.1 gives an overview of the outcomes at different TLV's. A multiplication factor of 0.8 was found to define the optimal TLV's, because the differences between the three groups were found to be the most significant (smallest average p-value). On top of that, the data in the three groups were optimally unambiguous, indicated by a very stable p-value, i.e. the smallest average standard deviation of the ten p-values.

Factor m	**REL**		**ACT**		**NEU**	**10 ANOVA's**	
	$x <$	**#songs**	$x >$	**#songs**	**#songs**	$\overline{m}$ **p-value**	$\overline{s}$ **p-value**
1.0	100.03	10	100.73	10	10	3.02E-05	2.71E-05
1.1	99.99	8	100.76	8	8	5.21E-05	4.84E-05
0.8	100.10	13	100.66	18	16	1.20E-08	7.77E-09

Table 2.1: Division into groups of activating, relaxing and neutral songs, according to different thresholds set by a multiplication factor m of σ.

2.3 Results

An analysis of the data is based on three parts. In the first part we analyse the kinematic data from the viewpoint of semantic classification. In the second part, we analyse the kinematic data from the viewpoint of audio-feature classification. In the third part, we consider the relation between kinematics and motivation.

2.3.1 Semantic classification

In order to obtain a music database with songs that have either an activating or relaxing character, we started from mood labels to select the songs from a large labeled music database. This was based on an association of activating and relaxing characteristics with known semantic labels (see Leman et al., 2013). Songs with mood labels “rebellious”, “bright”, “energetic”, “stimulating” or “happy” were expected to have an activating character. Songs labeled “peaceful”, “melancholy” or “romantic” were expected to have a relaxing effect on walking. However, we observed that a small amount of the mood labels obtained by means of semantic association (e.g., “passionate”, “emotional”, “mysterious”) were ambiguous with respect to their expected activating or relaxing character. For example, some songs associated with the label “emotional” sounded rather relaxing, whereas others sounded more activating. Nevertheless, despite the ambiguity of these labels, we decided to keep those songs in the database because the model that we are aiming at should be able to deal with this kind of ambiguity. After all, the goal of our research is to predict the (activating/relaxing) effect of a song on kinematic parameters from acoustic features, rather than from semantic labels. The semantic labels were only used to create a dataset that is sufficiently relevant for the kinematic effects that we predict.

However, it is of interest to make a comparison between the semantic labels and the actual kinematic response to the music, to check the relevance of our semantic labels post hoc. For this comparison in particular the ambiguous labels were left out.

A paired samples t-test was used to compare the kinematic differences. This test revealed that people walked significantly faster to music labeled as activating music (M = 100.64%, SE = 0.15) than to music labeled as relaxing music (M = 99.88%, SE = 0.14), $t(29) = -4.33$, $p < .001$, $r = .63$. A similar difference was found for stride length, where strides were larger for activating music (M = 100.54%, SE = 0.10) than for relaxing music(M = 100.08%, SE = 0.10), $t(29) = -3.60$, $p = .001$, $r = .56$.

A more in depth analysis was done by splitting the data in phase coherent and phase incoherent trials. Differences in walking behavior between activating and relaxing music were again checked with paired samples t-tests. On average, when people were not walking phase coherently with the musical beat, they walked significantly faster on music labeled as activating music (M = 100.96%, SE = 0.28) than to music labeled as relaxing music (M = 99.87%, SE = 0.26), $t(19) = -3.94$, $p < .001$, $r = .67$. The normalized stride length was also bigger for music labeled as activating (M = 100.66%, SE = 0.11), than for music labeled as relaxing (M = 100.12%, SE = 0.14), $t(19) = -2.80$, $p = .01$, $r = .54$.

However, when people were walking phase coherently with the musical beat, no significant differences in walking velocity between music labeled as activating (M = 100.34%, SE = 0.12) or relaxing (M = 100.13%, SE = 0.15) were found, $t(26) = -1.23$, $p = .23$, $r = .24$. This was also the case for stride length: music labeled as activating (M = 100.41%, SE = 0.13) versus music labeled as relaxing (M = 100.13%, SE = 0.14), $t(26) = -1.67$, $p = .11$, $r = .31$.

2.3.2 Audio-feature classification

The goal of this analysis is twofold: (i) can we separate songs in significantly different groups according to kinematic responses? and (ii) can we identify sonic features that are capable of predicting the kinematic response to a song? To answer those questions, we use the same approach of Leman et al. (2013) and Varewyck, Martens, and Leman (2013). As a first step, the audio feature extraction algorithm resulted in 185 energy and pitch related features per song. As a second step a regression model was trained (using a cross-validation method) to predict one output per song: a normalized stride length. Finally, a statistical analysis was performed: after dividing the songs in three groups (activating, neutral, and relaxing songs) - see Materials and Methods section - the actual normalized stride length values were compared.

Overall, the results of this analysis show that our model can predict the kinematic responses to songs. In the following paragraphs we discuss in more detail (i) the audio feature extraction, (ii) the regression model, and (iii) the statistical analysis.

Audio feature extraction. First, a frame-by-frame audio analysis was done on both pitch and loudness (total loudness and separate loudness in six frequency sub-bands). Second, these loudness and pitch feature values were analyzed in each IBI, giving rise to beat-level feature vectors. In total 46 sonic beat-level features were extracted. Examples are features describing the onset of a beat (e.g. the position of the onset within an IBI), features summarizing the loudness in an IBI (mean, standard deviation, and center of gravity of the loudness samples), features defining the notes in an IBI (salience and pitch of the first, second, and third most salient notes per IBI), and features reporting cosine similarities between two subsequent IBI's. Finally, for each of these 46 beat-level features the time pattern throughout the whole stimulus was analyzed, by checking evidences for increases or decreases of a feature value every two, three, four, or six beat periods. We refer to the study by Varewyck et al. (2013) for more details on the audio feature extraction.

Regression model: training and features. Participants were instructed to walk in their own preferred tempo, which on average was 112.47 SPM (*SD* = 7.23). Of the 84 songs in our database 81 were actually played to the participants. Sixty of the 81 songs were played to five or more participants. One of those songs was an unfamiliar song with a complex rhythm. Because this song was quite different from the other songs and the averaged normalized stride length was based on only five values, we decided to leave this song out. Therefore 59 songs were used for training and testing a predictive regression model for normalized stride length. The root-mean-square error (RMSE) between the normalized measured stride length and predicted values is 0.27. The Pearson Correlation Coefficient (PCC) between the two is 0.75, meaning that 56% of the original variance in the measurements is explained by the model.

Three features occurred in all 10 cross-validation tests, indicating that these features were most important in affecting the stride length. Table 2.2 summarizes them. Feature 159 shows the strongest correlation with the normalized stride length, explaining 28% of the variance (PCC = -0.53). The feature is derived from an analysis of the note evidences measured in subsequent IBI's. More precisely, this feature describes the frequencies (in chroma) of the third most salient pitch in each IBI. It has a high value if the spectral analysis of the temporal evolution of this feature reveals the clear presence of a frequency of one fourth of the beat rate, or once every period of four beats. The other two features are derived from an analysis of the individual loudness patterns in subsequent IBI's, i.e. the loudness evolution in time of six different loudness sub-bands. Feature 60 describes the average loudness in sub-band two for each IBI. It has a high value if the spectral analysis of the temporal evolution of this feature reveals the clear presence of a frequency of one sixth of the beat rate, in other words once every six beats. Feature 98 reflects the variance of loudness in sub-band six for each IBI. It has a high value if the spectral analysis of the temporal evolution of this feature reveals the clear presence of a frequency of one third of the beat rate, or once every three beats.

Id	**Feature description**	μc	σc	**N**	**PCC**
60	Evidence for a period of 6 beats in the average loudness in sub-band 2 in a beat period	-0.14	0.03	10	-0.47
98	Evidence for a period of 3 beats in the variance of the loudness in sub-band 6 in a beat period	-0.18	0.02	10	-0.50
159	Evidence for a period of 4 beats in the frequency (in chroma) in the third most salient note in a beat period (frequency=0 if no third note is present)	-0.18	0.05	10	-0.53

Table 2.2: The most frequently selected sonic features (out of ten models) for stride length. For each feature we list the feature number (Id), the mean (μc) and standard deviation (σc) of the regression coefficients for these features in the models, the number of times (N) the feature was selected, and the Pearson Correlation Coefficient (PCC).

All three of the above features have negative regression coefficients, which means that high feature values are associated with relaxed walking, or the use of less vigor in the walking movement. Features 60 and 98 reveal loudness fluctuations with frequencies of one sixth and one third of the beat rate respectively.

Analysis of the songs in our database reveals that such a ternary emphasis can either be found in songs with a ternary meter or by irregular patterns or longer melodies that divert attention from a binary emphasis in songs with a binary meter. The value of feature 159 is set to zero if only one or two notes are found in an IBI. Songs with the lowest values for this feature are songs with mainly drums and bass, like in hip-hop. The low values for this feature reveal the activating character of songs with little tonal diversity. This activating character could however be decreased by the presence of a more complex rhythmic structure, that weakens the binary emphasis.

Regression model: prediction. Since the regression model was based on stride length values, we only explored the effect of music type (relaxing, neutral, activating) according to the model on actual stride length and not on velocity. In addition, the factor of walking phase coherently or not was studied. Apart from stride length being normally distributed, $D(153) = 0.07$, $p = .07$, the variances were equal for the six factor groups, $F(5, 147) = 1.47$, $p = .20$. Hence, an ANOVA with stride length being the dependent variable was performed, where music type and stable phase walking were used as fixed factors. There was a significant main effect of music type on stride length, $F(2, 147) = 9.64$, $p < .001$. There was no significant main effect of stable phase on stride length, $F(1, 147) = 1.56$, $p = .21$, and no significant interactions were found, $F(2, 147) = 0.30$, $p = .74$. Tuckey post hoc tests revealed that stride length was significantly larger for neutral music (M = 100.40%, SE = 0.09) than relaxing music (M = 99.94%, SE = 0.10), $p = .004$, for activating (M = 100.54%, SE = 0.10) compared to relaxing music, $p < .001$, but not for activating compared to neutral music, $p = .60$. Fig. 2.2 clearly shows the difference between relaxing music and the other two types of music. Differences between neutral and activating music are smaller, even more so for walking with a stable phase than for walking phase incoherently.

2.3.3 Kinematics and motivation

After the walking experiment participants were asked to rate the motivational qualities of the music they had just heard. To find out whether the motivational aspects of the music were related to performance, i.e. velocity, the BMRI-2 scores of the trials during which participants walked slower to music than to silence were compared to the trials where they walked faster to music than to silence. The differences between the two groups of BMRI-2 scores were normally distributed. Therefore, a dependent t-test was used to calculate the differences between the two groups. When participants walked faster than in silence they rated the music significantly higher with the BMRI-2 test (M = 25.39, SE = 0.82) than when they walked slower than in silence (M = 22.74, SE = 1.21), $t(27) = -2.92$, $p = .01$, $r =$

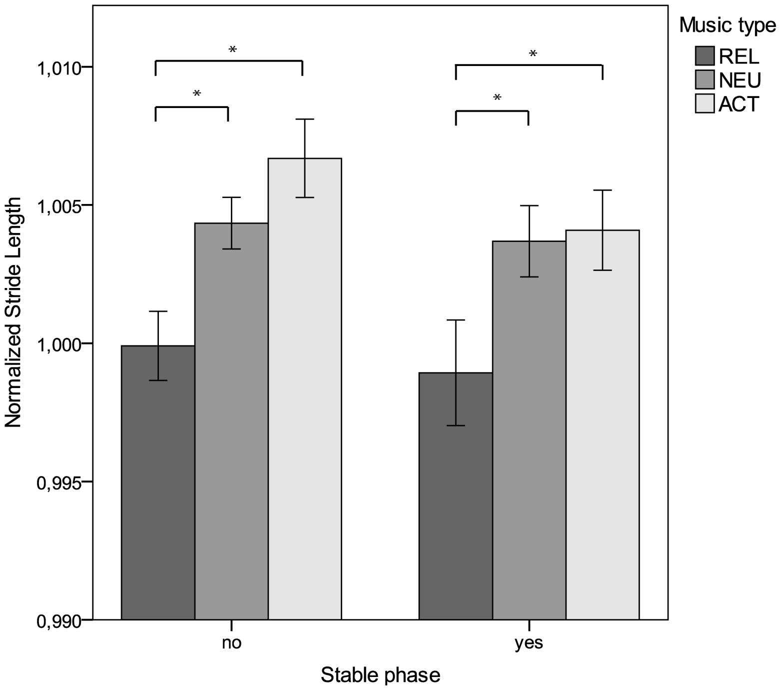


Figure 2.2: Normalized stride length for stable phase and non-stable phase walking. The figure depicts the normalized stride length values for different music types (REL, NEU, ACT) in stable phase trials and non-stable phase trials. A normalized stride length of value 1 represents an average stride length that equals the averaged stride length of walking in silence. Higher and lower values respectively indicate bigger or smaller stride length than in silence. Asterisks (*) indicate significance differences at p < .05.

.49.

We also explored a possible relationship between the motivational qualities of the music and the amount of phase coherence participants displayed while walking to music. The group of phase coherent trials was compared to the group of phase incoherent trials. Again, the differences between the two groups of BMRI-2 scores were normally distributed and a dependent t-test was performed. Walking in phase coherence with the music (M = 24.30, SE = 0.81) or not (M = 22.35, SE = 0.91) proved only to have a marginally significant influence on how the music was rated with the BMRI-2 test, $t(28) = -1.95$, $p = .07$, $r = .35$.

2.4 Discussion

This study shows that musical expression has an effect on people's walking velocity. Some music (called "activating") increases velocity, whereas other music decreases velocity. Results also confirm that sonic features can predict the size and the direction of the velocity effect of a song. In addition, the study shows that phase-coherence has only a minor effect on walking velocity and finally, it shows that the velocity effect goes together with a motivational effect.

2.4.1 Velocity effect of acoustic musical features on self-paced walking

Multiple studies underline the benefits of self-paced walking or exercise over moving at a prescribed tempo or intensity. A review by Williams (2008) states that there is emerging evidence that self-paced exercise elicits more positive affective responses than prescribed intensity training, and that affective response leads to increased adherence to exercise programs. Williams (2008) pleads for a shift in physical activity guidelines, emphasizing performance of exercise at an intensity that 'feels good' rather than at a specific prescribed intensity. This could result in a more sustainable training experience and enhanced health outcomes. Similar findings have been reported in the field of gait rehabilitation. A study by Roerdink et al. (2011) examined the use of different metronome rates in gait rehabilitation. They found superior auditory-motor coordination for pacing frequencies near the preferred cadence, suggesting that the efficacy of acoustic rhythms to influence gait degrades with pacing frequencies further away from one's preferred cadence. In addition, a review by Nombela et al. (2013) on rhythmic acoustic stimulation (RAS) for PD patients concludes that rhythms should be designed effectively, as they appear to lose therapeutic value when they are not tuned to the individual's pace, or when they become more cognitively demanding. They encourage individually tailored future neurological music therapies for PD, attending to the specific clinical features and stimulus responding of the individual.

The background for this lies in the tight link between velocity (v), step frequency (f) and step length (d). Kuo (2001) suggests that a person's preferred v-f relation is based on minimizing an O_2 consumption cost, and that this function can be captured by a mechanical model. As such, a given frequency has an effect on speed and therefore also on step length. Furthermore, Bertram and Ruina (2001), who also studied this v-f relationship, concluded that there are differences in v-f relationships depending on which kinematic parameter is constrained. Other studies show the difference in variability on step size as a result from walking at different step frequencies. A study by Styns et al. (2007) showed that walking at frequencies of 130 SPM or higher induced bigger differences in step size than walking with a lower cadence. In addition, Danion, Varraine, Bonnard, and

Pailhous (2003) showed a clear effect of stride frequency on the stride length variability. When instructed to walk at different prescribed step frequencies and step sizes, both spatial and temporal variability appeared to be minimal at a frequency of 120 SPM compared to lower frequencies of 96 or 107 SPM, or higher frequencies of 137 or 151 SPM. Danion et al. (2003) also propose a biomechanical explanation for longer steps having a higher consistency in step size: when taking large steps the joints get closer to their full flexion position, and muscles in the joints are stretched to their limits. Therefore, the larger the steps become, the less room there is to increase step size even further, thus decreasing irregularities of the stride. The above studies teach us to be careful with imposing a certain step frequency, especially if it is quite a bit higher or lower than a participant's preferred cadence.

Regarding the feature selection process, we do not claim that the used 185 sonic features describe the acoustical space of the songs optimally. It is likely that other features are useful as well. Our basic thought simply was to use a broad range of features describing temporal fluctuations in energy and pitch. Although our regression analysis selected different sonic features than the one in the study by Leman et al. (2013), results revealed that they represented similar characteristics in the music. In the current study as well as in the study by Leman et al. (2013), the audio features showed that a change or emphasis every four beats has an activating, i.e. increasing effect on walking velocity and stride length. The most activating songs in our study were mainly 4/4-meter songs of the genre Disco, Hip-hop, or New wave. These songs had clear audible beats and in general chord changes every four beats. On the other hand, most of the relaxing songs lacked a clear audible beat and came from genres like Down-tempo, Soul, and Jazz. The relaxing effect on kinematics could be explained by an emphasis on ternary aspects of the meter, such as in songs with a 3/4-meter, or songs with syncopating melodies. These features seem to counteract the regular flow of a binary walking pattern.

Within the feature set many features represented similar characteristics, e.g. mean energy in an IBI for different frequency sub-bands. In the feature selection process as described by Leman et al. (2013) only 10 of the 185 features are kept. The similarity between features resulted in quite similar feature values, which could easily have lead to other features coming out of the feature selection process. Another explanation for the selection of different features than in the study by Leman et al. (2013), could be traced back to the music database. In the current study, no classical music was used, whereas 13% of the music was classical in the study by Leman et al. (2013).

2.4.2 Phase coherence and the velocity effect

Musical rhythm has been shown to have a stimulative effect on the human locomotion irrespective of any synchronization (Priest, Karageorghis, and Sharp, 2004). Using synchronous music while exercising, proved to have even more benefits, such as longer endurance (Terry et al., 2012), less perceived exertion (Bood et al., 2013), and lower limb discomfort (Lim, Karageorghis, Romer, and Bishop, 2014). In the current study, approximately half of the participants walked with a stable phase relative to the music, even without instruction. This is quite different from the results of Mendonça, Oliveira, Fontes, and Santos (2014) and Franěk, van Noorden, and Režný (2014), where almost none of the participants synchronized with the music without instruction. A study by Van Dyck, Moens, Buhmann, Demey, Coorevits, Bella, and Leman (2015) offers an explanation for these differences. Runners were asked to run in their own tempo, while listening to music. First, the tempo of the music was matched exactly to the runner's cadence and was subsequently increased or decreased up to a maximum of 3%. A tempo entrainment basin was found: participants spontaneously adapted their running tempo to the tempo of the music, up to tempo changes of approximately 2%. The fact that participants in our study were presented with music at a tempo that exactly matched their walking tempo, will notably have contributed to the high number of synchronized trials. The music tempo in the studies by Mendonça et al. (2014) and Franěk et al. (2014) was matched more coarsely, augmenting the chance of having a tempo difference bigger than 2%, and thus making it harder for the music to have a subliminal effect on people's walking tempo.

Even though no significant main effect of stable phase on stride length was found, the results of our study showed that differences in stride length between the types of music were smaller for phase coherent walking, than for phase incoherent walking. In other words, the velocity effect of music was bigger for phase incoherent walking than for phase coherent walking. The difference in effect size emphasizes the distinction between the process of phase incoherent walking and phase coherent walking. The v-f relation can explain this: velocity can only be changed by the stride length if the cadence remains stable. However, when a person does not walk in phase coherence with the music, velocity can be changed both by changes in stride length and changes in cadence. A higher or lower cadence could in turn have an impact on the stride length. This interdependence results in a bigger variance in walking behavior, and thus a bigger effect size on walking velocity and stride length.

How these differences in motor behavior are linked to the auditory or neural system is not clear. None of the participants were instructed to synchronize their steps with the music. This is nevertheless no guarantee that they were not aware of the music and some of them might have consciously adapted their walking to the music. The dynamic re-parameterization of motor behavior while walking to music is the result of continuous neuro-feedback, and can either be a conscious or an unconscious process. Stephan, Thaut, Wunderlich, Schicks, Tian, Tellmann, Schmitz, Herzog, McIntosh, Seitz, and Hömberg (2002) studied the influence of awareness on sensorimotor synchronization behavior. Results showed that movements could be adjusted both at a subconscious level and at a fully conscious level. However, only fully conscious motor control which involves motor planning, activated dorsolateral prefrontal cortex. Future research might reveal whether awareness can explain the differences in movement behavior: either walking phase incoherently or with a stable phase.

2.4.3 Velocity effect and motivation

Our study revealed a significant relationship between the walking velocity and the motivational ratings (BMRI-2) (Karageorghis et al., 2006). Nevertheless, the relationship between walking in phase coherence and motivational scores was only marginally significant. The experimental setup with regard to measuring motivation has room for improvement. Instead of rating all the music after the walking experiment, the BMRI-2 scores might better reflect the motivational qualities of the songs when rated directly after hearing it during the exercise.

2.4.4 Velocity effect size

In this study we were able to confirm the earlier findings of Leman et al. (2013) on activating and relaxing music in ecological conditions (uninstructed self-paced walking with tempo-matched music). Nevertheless, the effect size on walking velocity, found in our study, was much smaller: up to 3% instead of up to 10%. Several explanations can be found for this discrepancy.

A first explanation concerns the difference in reference tempo. For most people, a cadence of 130 SPM is higher than their preferred self-paced cadence. According to the v-f relation, step sizes at self-paced tempo are larger, leaving less room to increase, whereas step sizes at higher tempi are smaller, thus leaving more room to increase. In other words, when step sizes are small the velocity effect of music can be larger.

A second explanation concerns the instruction. Only a small amount of studies have been dedicated to the effect of instructing people to synchronize, as opposed to spontaneous, or uninstructed synchronization. Two studies compared these differences in the field of social synchronization, more precisely in side-by-side walking. van Ulzen, Lamoth, Daffertshofer, Semin, and Beek (2008) explored the differences in amount of synchronization and phase locking, whereas Nessler and Gilliland (2010) studied the kinematic differences between individual walking, uninstructed side-by-side walking, and instructed side-by-side walking. The latter study revealed that instructed synchronization may promote a more active control strategy. This was shown by the use of more, but smaller steps in order to actively adapt one's walking pattern to another oscillating system. The results also showed an increase in the coefficient of variation for step size when instructed to synchronize, which could account for bigger effect sizes of music on step size when being instructed to synchronize to music. Additionally, instructed synchronization may have energetic considerations: healthy individuals adapt their stride length to their walking velocity to minimize energy expenditure (Zarrugh, Todd, and Ralston, 1974), suggesting that for rehabilitative purposes instructed synchronization would be less desirable.

A third argumentation for the smaller velocity effect of music is a difference in the walking protocol. In the present study people were asked to keep walking for two blocks of 15 minutes, without being instructed to synchronize. Whenever a new song started playing, a participant was already walking at the same tempo as the song's tempo. In the study by Leman et al. (2013) participants had to stop walking after each song. Even though they were instructed to synchronize their walking to the music, the stopping in between songs could have had an impact on participants' walking flow, resulting in bigger variances in step length. Another difference in experimental set-up concerns the reference stimulus. We compared the walking behavior of each song to the walking behavior on the 15 seconds of silence directly preceding each particular song. Leman et al. (2013) compared the walking behavior of each song to the average walking behavior on six metronome trials that were evenly distributed over the course of the experiment. If a person was walking at 130 SPM for 15 minutes, the step length might have decreased over the course of these 15 minutes, while the cadence stayed stable. As a consequence, comparing step size to the average metronome walking behavior, actually comes down to comparing with an average step size at the middle of the experiment, which could result in a bigger variance of normalized step size.

2.4.5 Relevance for gait rehabilitation

In the current study, an average increase in step length of 0.83% was found for walking on activating music. Since a decrease in step size is one of the major problems for Parkinson's disease (PD) patients, the use of RAS in the form of activating music is an interesting line of research for rehabilitative purposes for this group of patients. de Bruin, Doan, Turnbull, Suchowerksy, Bonfield, Hu, and Brown (2010) studied the use of music for walking rehabilitation with PD patients. They used highly familiar music for 30-minute walks, three times a week for a period of 13 weeks. A significant increase in stride length (0.70%) was found for patients with PD after the intervention period. An interesting path for future research might be to use activating familiar songs in a PD rehabilitation program, to try and increase stride length even more.

However, a study by Leow, Parrott, and Grahn (2014) concludes differently. Step size while walking to high- and low-groove music did not increase compared to walking without music. This effect could have been caused by the actual instruction to synchronize to the beat. PD patients are generally seen as weak beat perceivers (Leow et al., 2014), as their beat perception is impaired by deficient basal ganglia function. Requiring PD patients to synchronize their steps to the beat increases attentional demand, which could worsen their gait. Our study was limited in the sense that it tested healthy subjects. Still, the fact that an adequate type of music has the capacity to elicit a spontaneous increase in walking velocity and stride length, holds great promise for PD patients. Automatically synchronizing to a beat when not instructed to could nevertheless be debatable (Mendonça et al., 2014; Franěk et al., 2014; Nessler and Gilliland, 2010; van Ulzen et al., 2008).

Another reason why Leow et al. (2014) did not find an increase in stride length could be the type of music used in the experiment. We should be careful not to confuse high-groove music with activating music. High-groove music is said to “make you want to move”, to have danceable rhythms (Janata, Tomic, and Haberman, 2012). Stupacher, Hove, Novembre, Schütz-Bosbach, and Keller (2013) demonstrated that high-groove music modulates the motor system activity. The modulations of the motor system in musicians are aligned with the beat during high-groove music. However, activating the motor system does not necessarily result in an increased step length. It could also result in an increase of vigor in vertical movements or movements in the upper body such as in dancing. An important element of groove according to Madison and Sioros (2014) is syncopation: a disturbance in the regular flow of the rhythm, by placing accents where they would not normally occur. Such accentuation on the ‘off’ beat will however weaken a binary meter, which has been shown both in our study as in the study by Leman et al. (2013) to cause music to have a relaxing effect on walking.

Although music can increase people’s step size, for PD patients we need to pay special attention to the type of music that is most suitable to do so and we need to question the additional load by instructing them to synchronize.

2.4.6 Relevance in cyclic sports

Music has proven to positively influence athletes in all stages of exercise, from warm-up, to training and cool-down. Results from a study by Jarraya, Chtourou, Aloui, Hammouda, Chamari, Chaouachi, and Souissi (2012) demonstrated positive effects of music with a tempo between 120 and 140 BPM during warm-up on high intensity performances. The power output during exercise was significantly higher when music was presented during the warm-up as opposed to having no music in the warm-up phase. It would be interesting to see in future research if the power output would increase if only activating music would be presented. Music or rhythmic stimuli also proved to be beneficial after intense exercise. Eliakim, Bodner, Meckel, Nemet, and Eliakim (2013) found that the use of popular music at 140 BPM during recovery significantly increases the activity level (measured by the number of steps), lowers absolute lactate levels, and augments the average decrease in RPE. The use of activating and/or high-groove music will probably be most equipped to stimulate an active recovery.

During training, music can be used in several ways to prevent injuries and regulate training. Relaxing music could for instance be used in running training programs: without decreasing the runner's cadence, relaxing music could help runners to take smaller steps in order to prevent injuries caused by overstriding (Heiderscheit, Chumanov, Michalski, Wille, and Ryan, 2011). It could also be a tool in long distance running to enable to reduce heart rate, when it exceeds the anaerobic threshold, again without decreasing cadence. Other than preventing injuries, music can be used during training to enhance performance.

During a race it is not always permitted to use music. Nevertheless, the close link between our auditory and motor system shows promise to use auditory imagery as a way to improve our running performance during a race. A study by Meister, Krings, Foltys, Boroojerdi, Müller, Töpper, and Thron (2004) revealed that simply imagining playing a song on the piano activates similar brain areas as when actually playing the song. In analogy, if an athlete mostly trains with a specific song or playlist, simply thinking about these songs during a race could activate the motor system in similar ways as by actually hearing the songs.

As for gait rehabilitation, our results emphasize the importance of using an adequate type of music while performing. If the aim of training is to increase velocity, preferably, activating music should be used. The 1-2% velocity increase as a result of listening to activating music might seem small. However, if this increase in velocity would also be achievable for running, it would lead to a significant one-minute-win for a top athlete running a marathon. Future research in this area could reveal the actual velocity effect of activating music for top athletes.

2.4.7 Conclusions

Overall, our research question is highly relevant for the development of biofeedback systems in domains such as sports, rehabilitation, and healthy aging. Although uninstructed self-paced walking has multiple benefits, it is less likely to find a velocity effect of music, mainly because self-paced walking results in minimal variability in step size. Our study shows that the advantages of self-paced walking can go hand-in-hand with the spontaneous effect music has on walking velocity.

Furthermore, the current study proves the velocity effect of music for people that do not synchronize their step frequency with rhythmic acoustic stimuli, such as music. This opens up the possibility for using music for weak-beat perceivers, such as PD patients.

Finally, our study demonstrates a significant relationship between the motivational aspects of music and the velocity effect of music. Going towards a more individualized approach, this means that we can select music in advance that is both familiar and motivational for the participant in question, hence increasing the chances of music having an augmented effect on walking velocity.

My main contribution is: co-development of experimental design, co-execution of experiment, analysis of the data, and writing the paper.

3

Beat Synchronized Running and Motivation: an Investigation of Different Music-to-Movement Alignment Strategies

Buhmann, J., B. Moens, E. Van Dyck, D. Dotov, and M. Leman

Submitted

Abstract

The use of music and specifically tempo-matched music has been shown to affect running performance. Can we maximize the synchronization of movements to music and how does this influence kinematics and motivation? In this study we explored the effect of different types of music-to movement alignment on phase coherence, cadence, and motivation. Five different music-to-movement alignment techniques were tested and compared to a control condition where the music tempo deliberately was not aligned to the running cadence. Each strategy was tested during 5-minute runs, where 36 participants ran at their own comfortable pace. After running in silence for 25 seconds, five different songs with duration of 55 s were *played at the measured tempo. Music-to-movement alignment strategies that continuously adapt the beat timing to the footfall instant (relative phase angle), result in the highest phase coherence. In addition they elicit larger cadence decreases (M = -1.81% and -2.15% respectively) than the control condition (M = -0.53%). The results suggest that differences in cadence could be attributed to differences in timing of the beats (before or after the footfall instants). The strategy with the highest phase coherence was enjoyed more (Mdn = 71.38) than the control condition (Mdn = 67.25). The plausibility of beat timing having an effect on running tempo opens up possibilities for music-to-movement alignment techniques to optimize individual running cadence. In light of adherence to training programs, it is an advantage that the high-phase-coherence strategy was enjoyed more than the control condition.*

3.1 Introduction

Sports and exercise activities are generally believed to benefit from music listening under particular conditions: music has been shown to capture attention, raise spirits, trigger a range of emotions, alter or regulate mood, evoke memories, increase work output, heighten arousal, induce states of higher functioning, reduce inhibitions, and encourage rhythmic movement (Karageorghis and Priest, 2012a; Priest, Karageorghis, and Sharp, 2004). Effects of music during exercise can even be enhanced when certain types of music are considered (Buhmann, Desmet, Moens, Van Dyck, and Leman, 2016; Leman, Moelants, Varewyck, Styns, van Noorden, and Martens, 2013) and/or when a certain level of synchrony between the stimuli and the exercisers' movements occurs (Bood, Nijssen, van der Kamp, and Roerdink, 2013; Lim, Karageorghis, Romer, and Bishop, 2014; Ramji, Aasa, Paulin, and Madison, 2016; Terry, Karageorghis, Saha, and D'Auria, 2012). However, synchronizing one's movements with external auditory stimuli is not always a straightforward endeavour. Some people are more sensitive to sensorimotor adaptations in response to music than others, and generally, people either need to be instructed to synchronize or the tempo of the presented music needs to closely match the tempo of the exercise activity in order to maximize the level of auditory-motor synchronization. In short, within the scope of effects of music fall particularities of musical expression (e.g. groove (Janata, Tomic, and Haberman, 2012), activation/relaxation (Buhmann et al., 2016; Leman et al., 2013), human sensitivity to music and sensorimotor adaptation, and particular conditions of entrainment by which the effect can be triggered.

Given the fact that the running cadence depends on each person's capacity, this implicates that spontaneous synchronisation as an effect of sensorimotor adaptation is dependent on the individual exerciser and thus varies from person to person. Note that in previous research the preferred exercise intensity was often measured before the actual experiment, while in other cases the music tempo was matched rather coarsely to a subject's exercising tempo (e.g., within a 10% range of the assessed cadence) (Alter, O'Sullivan, Oh, Redelmeier, Marzolini, Liu, Forhan, Silver, Goodman, and Bartel, 2015; Franěk, van Noorden, and Režný, 2014). Unfortunately, such methods disregard the fact that the exercising tempo of an individual might be different at the time of the test or that his or her tempo might fluctuate during the test period. As a result, the contrast between the tempo of the music and the tempo of the exercise performance is likely to become too considerable to enable spontaneous entrainment.

A study by Van Dyck, Moens, Buhmann, Demey, Coorevits, Bella, and Leman (2015) unveiled that uninstructed synchronization of running cadence to musical tempo occurs spontaneously when the tempo of the music does not deviate more than 2.5% from the initial running cadence. This highlights that conditions of entrainment provide an affordance for sensorimotor adaptation to be effective. Other research that addresses the particular relations between entrainment conditions and sensorimotor adaptation is, however, scarce (Leman, 2016; Moens, Muller, van Noorden, Franěk, Celie, Boone, Bourgois, and Leman, 2014).

In this particular study we focus on very precise music-to-movement alignment strategies during running activity. Moens et al. (2014) describe four of such previously explored strategies. However, these alignment strategies were not compared within a single study and one test sample. The purpose of this study is, therefore, to fill this gap and to examine these alignment strategies in a randomized way, in order to try to re-validate earlier findings.

An alignment strategy (S0) is introduced where music and running performance behave in a completely allochronic fashion (in our case: music is played 20 beats per minute faster/slower than the assessed running cadence). This strategy is used as a control condition to compare against five other music-to-movement alignment strategies.

Two strategies involve the alignment of the music tempo to the runner's cadence. The tempo matching occurs either at the beginning of a song only (S1), or continuously throughout the exercise (S2). Tempo-matching alone, however, does not take into account the exact matching of the musical beats to the footfall instants. This can be achieved with a technique that employs relative phase angle manipulation: Steps and beats are recurring events, hence cyclic in nature. The difference in timing between a beat and the nearest footfall can be expressed with a relative phase angle (-180º to +180º), where a 0º angle indicates that the beat and footfall instant coincide exactly. Alignment strategies that employ such phase manipulation minimize the relative phase angle between the beat and footfall instant. In S3 the phase angle is minimized once, at the beginning of the exercise. The tempo of the music is however adapted continuously. The final two strategies involve continuous phase angle adaptation. S4 guides the runner towards perfect synchrony by adjusting the phase and hence tempo of the music at each step, thus at discrete timing intervals. However, in previous research, feedback from participants indicated that such a music adaptation sometimes felt unnatural or forced. Hence a new strategy is introduced (S5) based on adaptive oscillators (Hove, Suzuki, Uchitomi, Orimo, and Miyake, 2012), which results in continuous phase alignment using smoother tempo adaptations.

Our aim is to discover whether these different music-to-movement alignment strategies affect kinematics (cadence and speed) and/or motivation in distinct ways. In addition, the objective is to investigate possible gender differences in running performance. Research has shown that, when people are requested to rate motivational qualities of musical excerpts, women pay closer attention to the rhythmical qualities of the stimuli compared to their male counterparts (Karageorghis, Terry, and Lane, 1999). Besides, when female runners listen to their preferred musical stimuli, they tend to perform better than when they would have perceived non-preferred music. In comparison, musical preference does not seem to affect the performance of male exercisers (Cole and Maeda, 2015). Based on these results, we hypothesize to uncover a gender effect.

3.2 Methods

3.2.1 Participants

To establish sample size, a power analysis for a repeated-measures design was conducted using G*Power 3.1.9.2 (Faul, Erdfelder, Lang, and Buchner, 2007). Based on a small effect size with alpha set at .05 and power at .95, it was estimated that at least 28 participants would be required. In total, 36 healthy, adult participants (19 males) took part in the study. All participants were recreational runners (M_{age} = 31.22 years; SD_{age} = 8.13 years) and indicated to be capable of running 30 minutes continuously. Of all participants, 38.89% were trained in music (Pearson Chi-Square test showed no significant relation between gender and musical background, $\chi^2(1) = 1.22$, $p = .27$). In addition, about half of them (55.56%) reported to generally run without music, 22.22% indicated to usually run with music, and 22.22% ran both with and without musical accompaniment. The study was approved by the Ethics Committee of the Faculty of Arts and Philosophy of Ghent University and was in accordance with the statements of the Declaration of Helsinki.

3.2.2 Experimental design

Stimuli

A music database consisting of music tracks in the tempo range of 120-200 beats per minute (BPM) (the range of natural running cadence) was created. The database included musical stimuli from a previous running experiment (Van Dyck et al., 2015). Using the Brunel Music Rating Inventory-2 (BMRI-2) (see Karageorghis, Priest, Terry, Chatzisarantis, and Lane, 2006), all stimuli were rated as highly motivational for running. Additional tracks were selected to ensure complete coverage of the tempo range. In total, 43 tracks with clear beat information were selected. The tempo stability throughout each entire track was checked and quiet intros lacking clear beats were cut from the stimuli using Audacity (http://audacity.sourceforge.net). BeatRoot (Dixon, 2007) was applied to track the beats of each music track, while Adobe Audition (http://www.adobe.com) was used to normalize perceived loudness and minimize possible imbalances in sound pressure level.

Apparatus

Data was collected using a 7" tablet (Panasonic FZ-M1) running Windows 8.1, which was strapped to a backpack. In addition, a pair of sensors, headphones, and a management computer was employed. The tablet operated as the main hub that handled incoming sensor data and provided the musical stimuli. It was controlled remotely through the management computer, which was also employed to monitor the experiment in real-time.

To detect footfall instants, participants were equipped with two iPods (4th generation); one attached at each ankle. Using the Sensor Monitor Pro application on the iPods, data from accelerometers and gyroscopes was streamed wirelessly to the tablet at a sampling rate of 100 Hz. Speed measurements were performed using a sonar system (MaxBotix LV-MaxSonar-EZ: MB1010) connected to the tablet through a Teensy 3.1 micro-controller. It detected marker rods of 1.90 m high, placed at a regular interval of 10 m around the running track. Through computation of the time it took to cover each interval, absolute speed was determined. The analogue signal was sampled at 30 Hz and digitized using the Teensy.

The wireless connection between the tablet, iPods, and management computer was provided through a Wi-Fi router (TP-Link M5360), firmly strapped to the backpack, ensuring reliable communication between all crucial components. The management computer was applied to initiate the experimental sessions and to monitor sensor data in real-time. Musical tempi were manipulated using a phase vocoder, which time-stretched the music without modifying pitch. The system logged all data and calculations in real-time. Music tempo was adapted based on the selected alignment strategy [for the implementation of the music alignment strategies, see Moens et al. (2014)]. Finally, the aligned music was sent back to the participant using Sennheiser HD60 headphones connected to the tablet.

Procedure

All experiments took place in the Flanders Sports Arena of Ghent, Belgium. After being equipped, participants were asked to run on a 200 m running track for five minutes continuously, and this for six consecutive times. In each of the six 5-minute runs, a different alignment strategy was tested and it was ensured that all orders could occur only once. A summary of the different strategies is provided in Table 3.1.

Participants were instructed to run at their own comfortable pace. No information was distributed concerning the purpose of the experiment and all participants ran in solo conditions. After each 5-minute run, participants were allowed to take a break for several minutes in which they rated their perceived exertion (RPE) on the Borg Scale (Borg, 1998). In addition, they rated the level of physical enjoyment on the 8-item version of the Physical Activity Enjoyment Scale (PACES) (Kendzier-

Strategy	Type of music adaptation
S0	Allochronic music (tempo differs at least 20 BPM from cadence), making it impossible to synchronize gait to music.
S1	One-time tempo matching at the beginning of a song.
S2	Continuous tempo adaptation so BPM matches SPM each step.
S3	Continuous tempo adaptation and in-sync phase start.
S4	Forced phase synchronisation by continuous tempo alignment and phase adjustment, updated each step.
S5	Forced phase synchronisation by continuous tempo and phase alignment, updated using adaptive oscillators.

Table 3.1: Descriptions of all the tested music-to-movement strategies.

ski and DeCarlo, 1991; Mullen, Olson, Phillips, Szabo, Wójcicki, Mailey, Gothe, Fanning, Kramer, and McAuley, 2011), a single factor scale to assess the level of enjoyment during a physical activity in adults across exercise modalities.

Each of the 5-minute runs started with 25 seconds of silence, followed by five musical excerpts of equal length (55 s) with an original tempo approaching the average cadence of the last seven footsteps. Musical tempo was then manipulated based on the selected alignment strategy.

3.2.3 Gait related measurements

Cadence and velocity

We examined the effect of the different alignment strategies on kinematic parameters such as cadence and velocity. Average cadence and velocity values during music playback are compared to those in the preceding 25 s of silence. The resulting dependent variables are reflected as percentages, where zero indicates no difference, while a negative or positive value indicates a respective decrease or increase in cadence or velocity compared to the silent part of the condition.

Synchronization

The level of synchronicity with the music, or rather, the stability of the relation between a runner's footfall and the musical beat, is typically represented by the resultant vector length. This is a measure of tempo entrainment, ranging from zero to one with one representing perfect entrainment (Mormann, Lehnertz, David, and Elger, 2000). In addition, the average relative phase angle reveals whether footfall instants occur before the beat is played (negative phase) or after (positive phase).

Comparisons (*Mdn*)			*z*	*p*	*r*
S0 (0.05)	x	S1 (0.70)	-5.232	< .001	-.87
		S2 (0.82)	-5.160	< .001	-.86
		S3 (0.82)	-5.232	< .001	-.87
		S4 (0.89)	-5.232	< .001	-.87
		S5 (0.94)	-5.232	< .001	-.87
S1 (0.70)	x	S3 (0.82)	-3.653	< .001	-.61
		S4 (0.89)	-4.996	< .001	-.83
		S5 (0.94)	-5.130	< .001	-.86
S2 (0.82)	x	S4 (0.89)	-4.022	< .001	-.67
		S5 (0.94)	-4.930	< .001	-.82
S3 (0.82)	x	S4 (0.89)	-2.970	.003	-.50
		S5 (0.94)	-4.619	< .001	-.77
S4 (0.89)	x	S5 (0.94)	-4.572	< .001	-.76

Table 3.2: Significant differences in phase coherence (resultant vector length R): Wilcoxon signed-rank tests comparing all six alignment strategies with each other.

3.2.4 Data analysis

Each of the five tempo-matched music-to-movement alignment strategies was compared to the allochronic control strategy. Depending on how the data were distributed, the analyses were either performed with repeated measures ANOVA or Friedman's ANOVA tests.

3.3 Results

3.3.1 Synchronization

A Friedman's ANOVA showed a main effect of the strategy on resultant vector length, $\chi^2(5) = 120.982$, $p < .05$. Wilcoxon tests were used to follow up this finding. A Bonferroni correction was applied and so all effects are reported at a .003 level of significance. Results reveal that all six strategies differ with respect to the resultant vector length, except S1 versus S2 and S2 versus S3. All significant differences are summarized in Table 3.2. Figure 3.1 visualises the phase coherence per alignment strategy by showing the distribution of all relative phase angles: the more dense the distribution, the larger the resultant vector length.

3.3.2 Cadence

One of the dependent variables of interest is the change in cadence from running in silence to running with music. A 2x6 mixed-design ANOVA test with gender

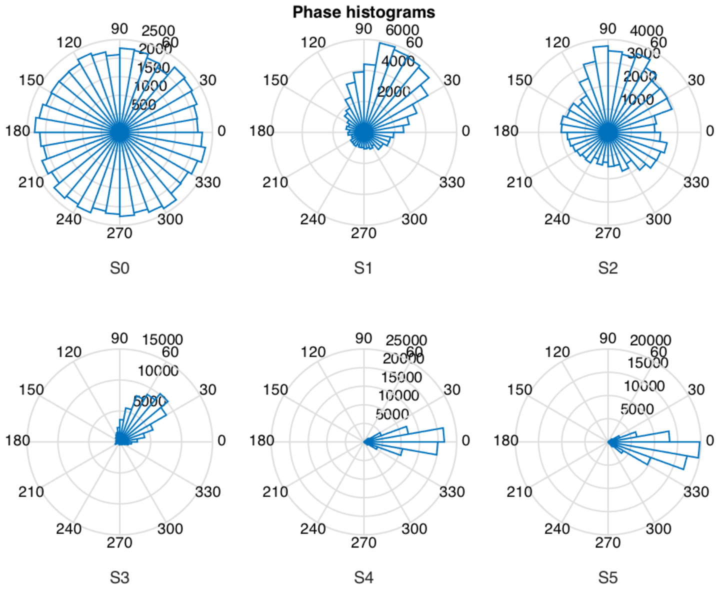


Figure 3.1: Phase angle histograms or polar plots of the six different alignment strategies: differences in timing between the moments of the footfall and beat are represented on a scale of 0º to 360º, where a 0º angle indicates a perfect match

(male, female) as between-subjects variable and condition (S0 to S5) as within-subjects variable revealed a significant main effect of the strategy on the change in cadence, *F*(5, 170) = 16.46, $p < .001$. Contrasts revealed that for S4, *F*(1, 34) = 17.23, $p < .001$, $r = .58$, and S5, *F*(1, 34) = 29.48, $p < .001$, $r = .68$, running cadence decreased significantly more (M = -1.81%, *SE* = 0.37, and M = -2.15%, *SE* = 0.34 respectively) compared to S0 (M = -0.53%, *SE* = 0.27).

There was no significant main effect of gender, indicating that on average there were no significant differences in change in cadence between male (M = -1.06%, *SE* = 0.15) and female participants (M = -0.93%, *SE* = 0.22), *F*(1, 34) < 1, $p = .78$, $r = .05$.

An interaction effect between the strategy and the gender of the participant was observed, *F*(5, 170) = 4.97, $p < .001$, indicating that the change in cadence differed between men and women for different strategies. Contrasts were performed, revealing interaction effects between gender x S0 x S4, *F*(1, 34) = 9.10, $p = .005$, $r = .46$, and gender x S0 x S5, *F*(1, 34) = 6.40, $p = .016$, $r = .40$. This indicated that although, for both males and females, cadence decreased substantially during S4 and S5 compared to S0, this decrease is more pronounced for female runners (Figure 3.2).

3.3.3 Speed

No main effect of the type of strategy on change in speed was uncovered, *F*(5, 165) = 1.02, $p = .407$, nor was there a significant main effect of gender, *F*(1, 33) = 1.36, $p = .25$, $r = .20$. Besides, there was no interaction effect between strategy and gender, *F*(5, 165) = 2.16, $p = .061$.

3.3.4 Motivation

Wilcoxon signed-rank tests (comparing each strategy with S0) were performed on the scores of the PACES scale. A Bonferroni correction was applied and so all effects are reported at a .01 level of significance. The motivational scores were higher for S5 (*Mdn* = 71.38) compared to S0 (*Mdn* = 67.25), $T = 187$, $p = .008$, $r = -.31$. None of the other strategies displayed significant differences in motivation when compared to the allochronic strategy (S0).

3.4 Discussion

Similar to earlier research (Moens et al., 2014) we were able to induce various levels of synchronization using different music-to-movement alignment strategies. As a matter of fact, the synchronization was most prominent and stable in case of continuous adaptation of the timing of the beats (resulting as a consequence in

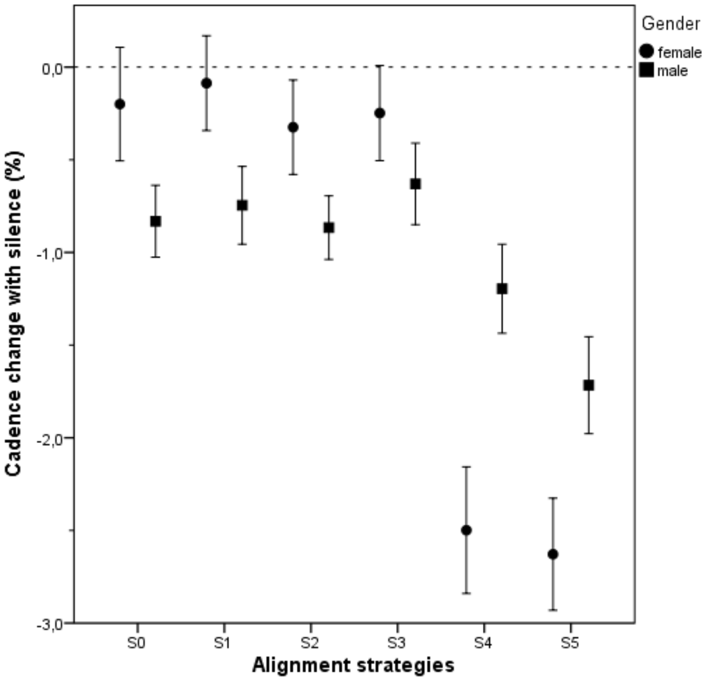


Figure 3.2: Cadence change with respect to initial silence (%) per gender and alignment strategy.

continuous music tempo adaptation), to the footfall instants of the human subject running. In addition, both strategies employing this method (S4 and S5) elicited decreased cadence rates compared to the strategies facilitating lower degrees of synchronization. Results also revealed that decreases in cadence for S4 and S5 were more pronounced for female than for male subjects. Finally, higher levels of assessed motivation were uncovered for S5 compared to the allochronic strategy (S0), where no synchronization with the music could be achieved.

3.4.1 Lower cadence

In this particular study, no difference in cadence change was found between the allochronic strategy (S0) and S1, S2, and S3. However, results unveiled lower levels of running cadence for S4 and S5 when compared to S0. The difference between S4 and S5 on the one hand and S1, S2, and S3 on the other consists of the continuously adapted phase angle in the former two strategies, while in the latter three strategies the phase angle is either not considered or beat and footfall instants are merely aligned at the start of the experimental condition.

Continuously manipulating the relative phase angle implies the introduction of every subsequent beat at the predicted moment of the next footfall instant, or in other words, the reduction of the relative phase towards 0º. This is well reflected in the measured average relative phase angles of S4 and S5 (0º and -8º respectively). Different results were obtained for condition S1, S2, and S3, with average relative phase angles of respectively 58º, 62º, and 51º. As such, it could be suggested that the different average relative phase angles can explain differences in cadence: it is likely that placing the beats before the predicted footfalls has the opposite effect on cadence than when placing the beats after the predicted footfall instants.

Introducing musical beats right after each footfall instant is reflected by negative relative phase angles. This could stimulate a runner to increase the duration between his/her steps and slow down his/her tempo to try to obtain perfect synchronization with the musical stimulus. On the contrary, the introduction of the beat prior to the footfall instant (positive phase) might rather induce a feeling of 'being late', which could in turn stimulate the runner to speed up.

A limitation of our study is the absence of a reference condition where participants ran in silence. Such a condition might have provided us with some insight into the 'natural' running behaviour of our participants. Currently, it remains unclear whether the lower cadence demonstrated in S4 and S5 is a result of the decrease in natural tempo due to the negative phase angle, or if this tempo is in fact similar to participants' natural tempo while the positive phase angle in S1, S2, and S3 might be held accountable for an acceleration in running tempo.

Either way, our results seem to reveal that the average relative phase angle affects running cadence. Future studies might examine the hypothesis that a negative phase slows runners down while a positive phase speeds them up and trace the exact instant where the measured zero phase coincides with the perceived zero phase. The possibility that the perceived zero phase (perfect synchrony) can be different across individuals might be considered as well.

3.4.2 Gender

On the subject of gender, a more pronounced change in cadence for female runners was observed. It seems that, compared to their male counterparts, women demonstrated lower levels in cadence with S4 and S5, and higher ones when running with S1, S2, and S3. This is in line with research by Karageorghis et al. (1999), stating that women pay more attention to the rhythmical characteristics of music than men do.

3.4.3 Music-effort-motivation loop

Not only can moving in synchrony with music have psychophysical and physiological benefits (Bood et al., 2013; Lim et al., 2014; Ramji et al., 2016; Terry et al., 2012), it might also evoke a sense of agency (Fritz, Hardikar, Demoucron, Niessen, Demey, Giot, Li, Haynes, Villringer, and Leman, 2013). The slightly negative average phase angle in S5 tells us that footfall instants occur just prior to the beats and that this happens with great consistency, as reflected by a large resultant vector length. Although participants are not producing the music themselves, such a stable and slightly negative phase might evoke a feeling as if they are in control of the beats, often referred to as *agency*. In combination with a certain amount of physical exertion, this feeling of agency might contribute to a perceived positivity bias (Fritz, Schneider, and Villringer, 2016) or a feeling of homeostasis (Leman, 2016) which could possibly explain the higher motivational ratings in S5 compared to the allochronic strategy (S0). However, more research on this matter is needed in order to draw more definite conclusions.

To conclude, our results show that a continuous phase alignment strategy is capable of impacting cadence. Future research with specific cadence target values in mind could employ such strategies. Research by Reenalda, Maas, and de Koning (2016) illustrates that each runner exercises at his or her own preferred cadence and this cadence often differs from the runner's individual optimal running cadence. Our work provides a possible starting point to use music-to-movement alignment strategies in order to support exercisers to optimize their running cadence.

3.5 Practical implication

Music-to-movement alignment strategies enable us to continuously and closely follow a person's behavioural response to music. This is of great value for sports and rehabilitation programs where music-based biofeedback is employed to improve individual performance (Maes, Buhmann, and Leman, 2016). In the future, the aim is to adapt our alignment strategies and introduce musical beats either slightly before or after the predicted footfalls. Such strategies could open up possibilities to spontaneously (and imperceptibly) optimize an individual's cadence and step size (Reenalda et al., 2016).

My main contribution is: co-development of experimental design, co-execution of experiment, co-analysis of the data, and co-writing the paper (Method section).

4

Spontaneous Entrainment of Running Cadence to Music Tempo

Van Dyck, E., B. Moens, J. Buhmann, M. Demey, E. Coorevits, S. Dalla Bella, and M. Leman

In *Sports Medicine - Open*, 2015, *1*, 1-14.

Abstract

Since accumulating evidence suggests that step rate is strongly associated with running-related injuries, it is important for runners to exercise at an appropriate running cadence. As music tempo has been shown to be capable of impacting exercise performance of repetitive endurance activities, it might also serve as a means to (re)shape running cadence. The aim of this study was to validate the impact of music tempo on running cadence. It was examined whether runners would spontaneously entrain their running cadence to changes in music tempi and whether a basin for unintentional entrainment of running cadence to music tempo could be discovered. Sixteen recreational runners ran four laps of 200 m (i.e. 800 m in total); this task was repeated 11 times with a short break in between each four-lap sequence. During the first lap of a sequence, participants ran at a self-paced tempo *without musical accompaniment. Running cadence of the first lap was registered and during the second lap, music with a tempo matching the assessed cadence was played. In the final two laps, the music tempo was either increased/decreased by 3.00%, 2.50%, 2.00%, 1.50%, 1.00%, or was kept stable. This range was chosen since the aim of this study was to test spontaneous entrainment (an average person can distinguish tempo variations of about 4%). Each participant performed all conditions. Imperceptible shifts in musical tempi in proportion to the runner's self-paced running tempo significantly influenced running cadence ($p < .001$). Contrasts revealed a linear relation between the tempo conditions and adaptation in running cadence ($p < .001$). In addition, a significant effect of condition on the level of entrainment was revealed ($p < .05$), which suggests that maximal effects of music tempo on running cadence can only be obtained up to a certain level of tempo modification. Finally, significantly higher levels of tempo entrainment were found for female participants compared to their male counterparts ($p < .05$). The applicable contribution of these novel findings is that music tempo could serve as an unprompted means to impact running cadence. As increases in step rate may prove beneficial in the prevention and treatment of common running-related injuries, this finding could be especially relevant for treatment purposes, such as exercise prescription and gait retraining.*

4.1 Background

Approximately 56% of recreational runners sustain a running-related injury each year (van Gent, Siem, van Middelkoop, van Os, Bierma-Zeinstra, and Koes, 2007). About 50% of all running-related injuries occurs at the knee and are most often due to the inability of the lower extremity joints to adequately control the loads applied during initial stance (Taunton, Ryan, Clement, McKenzie, Lloyd-Smith, and Zumbo, 2002; Ferber, Noehren, Hamill, and Davis, 2010; Noehren, Davis, and Hamill, 2007). A number of strategies designed to reduce loads to these joints have been suggested, with one of the most common ones applying an increased step rate. Subtle increases in step rate have for instance been shown to substantially reduce the loading to the hip and knee joints during running and may therefore prove beneficial in the prevention and treatment of common running-related injuries (Heiderscheit, Chumanov, Michalski, Wille, and Ryan, 2011). However, less is known about the specific strategies that can be employed to change step rate. In this study, a novel strategy using music as a tool to impact step rate is examined. The means by which music might serve as an adequate tool for manipulating running cadence, is discussed below.

A great deal of runners exercise while listening to music. This should not come as a surprise, since music listening during sport activities is believed to capture attention (Priest and Karageorghis, 2008), distract from fatigue and discomfort (Yamashita, Iwai, Akimoto, Sugawara, and Kono, 2006), prompt and alter mood states (Edworthy and Waring, 2006; Shaulov and Lufi, 2009), enhance work output (Rendi, Szabo, and Szabó, 2008; Priest, Karageorghis, and Sharp, 2004), increase arousal (Lim, Karageorghis, Romer, and Bishop, 2014), relieve stress (Särkämö, Tervaniemi, Laitinen, Forsblom, Soinila, Mikkonen, Autti, Silvennoinen, Erkkilä, Laine, et al., 2008), stimulate rhythmic movement (Atkinson, Wilson, and Eubank, 2004), and evoke a sense of power and produce power-related cognition and behaviour (Hsu, Huang, Nordgren, Rucker, and Galinsky, 2015). Simpson and Karageorghis (2006), for instance, examined the effect of music on a 400 m sprint performance while controlling for pre-performance mood. It was shown that music resulted in better sprint performance compared to the no music control. In another study, Styns et al. (2007) observed that participants walked faster with music than with metronome ticks, while Bood et al. (2013) showed that time to exhaustion was significantly longer with acoustic stimuli than without when participants were asked to run to exhaustion on a treadmill. Results of studies such as these suggest that music could be applied to physical activities, such as walking or running, with a considerable positive effect.

The idea that music can serve as a strategy for coping with physical exertion has been linked to the *parallel processing model*, which focuses on the limited human attention capacity (Rejeski, 1985; Nethery, 2002). This implies that the focus of an exerciser is shifted to external events in an effort to reduce the perception of neural exertion signals coming from the muscles, joints, and cardiopulmonary systems (Tenenbaum and Hutchinson, 2007). However, it appears that external musical cues can only be the focus of attention in the case of low-to-moderate physiological awareness and perceived exertion. When the workload becomes too high, the exerciser's attention is typically shifted towards the painful or fatiguing effects of the exercise (Rejeski, 1985; Nethery, 2002; Tenenbaum, 2005; Razon et al., 2009; Hutchinson and Tenenbaum, 2007). In general, music has shown to be most effective to exert ergogenic and distractive effects when it is used to accompany self-paced exercise (Edworthy and Waring, 2006; Karageorghis, 2008; Cohen et al., 2007; Elliott et al., 2005). In addition, it is believed that particularly motivational music can successfully uplift mood state and increase work capacity (Shaulov and Lufi, 2009; Karageorghis et al., 2009; Terry et al., 2012).

Besides the motivational factor, exercise that is repetitive in nature is believed to benefit mostly from music that is synchronized with the tempo of the exerciser's movements; endurance can be extended and performers exercise at higher intensities when moving in synchrony with musical stimuli (Terry et al., 2012). It has been suggested that this effect of synchronized music is due to its ability to reduce the metabolic cost of exercise by enhancing neuromuscular or metabolic efficiency (Karageorghis et al., 2009; Kenyon and Thaut, 2003). Regular corporeal patterns demand less energy to imitate, due to the lack of timely adjustments within the kinetic pattern, but also because of an increased level of relaxation resulting from the precise expectancy of the forthcoming movement (Smoll and Schutz, 1982). As such, a point of reference is created that is able to attract and swiftly entrain recurring motor pattern efficiency (Kenyon and Thaut, 2003; Rossignol and Jones, 1976). Synchronization is typically understood as an intentional mechanism, which is highly task constrained (Richardson, Marsh, and Schmidt, 2005). Most previous research on the impact of synchronized music on exercise performance generally focused on instructed or imposed synchronization, e.g. (Lim et al., 2014; Simpson and Karageorghis, 2006; Styns et al., 2007; Bood et al., 2013; Terry et al., 2012). However, it is also the case that synchronization can occur spontaneously (Richardson et al., 2005). Previous studies have highlighted the natural or spontaneous predisposition of humans to respond to rhythmical qualities of music (Karageorghis et al., 1999; Large, 2000), but much less is known about the capabilities of exercisers, and especially runners, to spontaneously synchronize with the tempo of musical stimuli. Yet, spontaneous entrainment of one tempo with another is only believed to occur when the strength of the coupling is able to overcome possible contrasts in natural movement period or tempo (Von Holst, 1973). For a given coupling strength, unintentional entrainment only occurs within a specific range of period differences, reflecting the system's entrainment basin (Richardson, Marsh, and Schmidt, 2005; Lopresti-Goodman, Richardson, Silva, and Schmidt, 2008; Schmidt and Richardson, 2008; Schmidt, Richardson, Arsenault, and Galantucci, 2007; Strogatz, 1994).

The effect of music on repetitive endurance activities also depends on the specific tempo of the musical stimulus. Waterhouse et al. (2010) revealed that cyclists' covered distance, power, and pedal cadence increased when faster music was presented, while slowing down the music tempo resulted in decreases of these measures. Edworthy and Waring (2006) explored the effect of music tempo (and loudness) on treadmill running and demonstrated that an increase in the tempo, and to a lesser extent the loudness of the stimulus, resulted in an increase in running speed. In the light of findings such as those described above, it is quite plausible that music tempo could also serve as a means to influence running cadence. And as a link between step rate and hip and knee joint loading has been established before (Heiderscheit et al., 2011), results of this study could be particularly relevant with regard to the prevention and treatment of running-related injuries.

The aim of this study was to validate the impact of music tempo on running cadence. We hypothesized that recreational runners would adapt their self-paced running cadence to imperceptible changes in musical tempi and, thus, entrain spontaneously with the music tempo. Furthermore, we believed that the degree of entrainment would decrease with increasing changes in music tempo and, thus, that a basin for unintentional entrainment of running cadence to music tempo exists. As it has been shown that unintentional coordination typically manifests as relative or intermittent coordination (i.e. movements are attracted to a 0 or 180º but are not phase locked) (Von Holst, 1973; Lopresti-Goodman et al., 2008; Kelso, 1995), rather than phase-locked steps, *entrainment* refers to the amount of steps taken in a tempo sufficiently close to the music tempo (max. 1% difference between running cadence and music tempo). Besides, since previous research often reported better results for women compared to men regarding music-to-movement coordination (Priest et al., 2004; Van Dyck et al., 2013), we expected female participants to display larger levels of entrainment. Finally, as it has been demonstrated that only when physiological awareness and perceived exertion are relatively low that music can distract from fatigue and discomfort (Rejeski, 1985; Tenenbaum, 2005), the relationship between the level of entrainment and the degree of perceived exertion was examined.

4.2 Methods

4.2.1 Ethics statement

The study was approved by the Ethics Committee of the Faculty of Arts and Philosophy of Ghent University, and all procedures followed were in accordance with the statements of the Declaration of Helsinki. In addition, all participants signed a form to declare that they participated voluntarily; that they had received sufficient information concerning the tasks, the procedures, and the technologies used; that they had the opportunity to ask questions; and that they were aware of the fact that running movements were measured, for scientific and educational purposes only.

4.2.2 Participants

To establish sample size, a power analysis for a repeated-measures design was conducted using G*Power 3.1.9.2 (Faul, Erdfelder, Lang, and Buchner, 2007). Based on the effect sizes reported in comparable studies (Simpson and Karageorghis, 2006; Bood et al., 2013; Karageorghis et al., 2009), the analysis indicated that minimally 14 participants for an α of 0.05 and a power of 0.80 would be required. Sixteen healthy adult participants (nine females) took part in the study. The test group consisted of recreational runners with an average age of 22.25 years (*SD* = 2.14), a mean body mass of 66.56 kg (*SD* = 9.32), and an average height of 1.74 m (*SD* = 0.10), who reported to be fit to run about 10 km. The majority (62.50%) had received musical training (Fisher's exact test showed no significant association between gender and musical background, $\chi^2(1) = 2.05$, $p = .30$). All participants reported that running is an activity that forms a part of their lives, with varying degrees of frequency (12.50% runs multiple times a week; 56.25% runs about once a week; 31.25% runs about once a month; 0% runs about once a year or not at all). Of all participants, 50% reported to typically train with music, 32.25% generally runs without music, and 18.75% runs both with and without musical accompaniment.

4.2.3 Stimuli

Previous research indicated that the natural running cadence for recreational runners lies somewhere between 130 and 200 steps per minute (SPM) (Karageorghis, Terry, Lane, Bishop, and Priest, 2012). On that account, a music database consisting of songs in the tempo range of 130–200 beats per minute (BPM) was created. A group of 19 students from Ghent University, all recreational runners, were asked to provide a list of at least ten songs they believed to be motivational to run to. From that specific list of music, the database for the experiment was created. In total, 117 songs with a clear beat and correct tempo range were pre-selected (see Table 4.1). In the course of the selection process, it was verified that the tempo of each song remained stable throughout the entire track. Using Audacity software (http://audacity.sourceforge.net), intros without clear beats were cut from the stimuli. BeatRoot (Dixon, 2007) was applied to track the beats of each song in order to ensure that only songs between 130 and 200 BPM were included, while ReplayGain was used to normalize perceived loudness and minimize possible imbalances in sound pressure level.

Table 4.1: List of all musical stimuli.

ID	Artist	Song	Label(s)	Year published	Tempo (BPM)
1	Epica	Illusive Consensus	Transmission	2003	132
2	Gregory Porter	On My Way to Harlem (Radio Edit)	Motema	2012	138
3	Interpol	Slow Hands	Matador	2004	139
4	The Supremes	I Hear a Symphony	Motown	1965	139
5	Van Halen	Ain’t Talkin’ ’Bout Love	Warner Bros	1978	139
6	Combichrist	Electrohead	Out of Line/Metropolis	2007	140
7	dEUS	The Soft Fall	PIAS	2012	140
8	P!nk	Who Knew	LaFace	2006	140
9	Noisettes	Never Forget You	Mercury/Vertigo	2009	141
10	Rammstein	Benzin	Motor	2005	142
11	Royksopp	Tricky Tricky	Astralwerk/EMI	2009	142
12	Deftones	My Own Summer (Shove It)	Maverick/Warner Bros	1997	143
13	16 Horsepower	Outlaw Song	Jetset	2006	144
14	Coldplay	In My Place	Parlophone	2002	144
15	The Hickey Underworld	Future Words	PIAS	2009	145
16	ABBA	Waterloo (English Version)	Polar/Epic	1973	146
17	Steppenwolf	Born to Be Wild	Dunhill/RCA	1967	146
18	The Sisters of Mercy	Alice	Merciful Release	1982	146
19	School Is Cool	The World Is Gonna End Tonight	Not on label	2011	147
20	Tom Odell	I Know	Columbia/In the Name Of	2012	147
21	Trixie Whitley	Irene	Unday Records	2013	147
22	Aphex Twin	Flim	Warp/Sire/WEA	1997	148
23	Bruce Springsteen	Dancing In the Dark	Columbia	1984	148
24	Nneka	Heartbeat	Yo Mama’s Recording	2008	148
25	Alt-J	Breezeblocks	Infectious	2012	149
26	Marco Borsato	Ik leef niet meer voor jou	Polydor	1995	149
27	A Perfect Circle	Thinking of You	Virgin	2000	150
28	Editors	An End Has a Start	Kitchenware/FADER	2007	150
29	Florence and The Machine	Dog Days Are Over	Island	2009	150
30	Guns N’ Roses	It’s So Easy	Geffen Records/Interscope	1987	150
31	Katy Perry	E.T.	Capitol	2010	150

Table 4.1: List of all musical stimuli (Continued).

ID	Artist	Song	Label(s)	Year published	Tempo (BPM)
32	Pearl Jam	Lightning Bolt	Monkeywrench/Republic	2013	151
33	The Killers	Spaceman	Island/Vertigo	2008	151
34	Bloc Party	Flux	Wichita/Vice	2007	152
35	Elton John	Saturday Night's Alright (For Fighting)	MCA/DJM	1973	152
36	P!nk	Are We All We Are	RCA	2012	152
37	De Staat	Sweatshop	Cool Green Recordings	2011	153
38	Ike & Tina Turner	Nutbush City Limits	United Artists	1973	153
39	Kings of Leon	Sex On Fire	RCA	2008	153
40	OutKast	B.O.B.	LaFace/Arista	2000	153
41	The Black Eyed Peas	Pump It	Interscope	2005	153
42	Massive Attack	Teardrop	Circa/Virgin	1998	154
43	Kaiser Chiefs	Never Miss a Beat	B-Unique/Universal	2008	155
44	Morphine	Honey White	Rykodisc	1995	155
45	The Pipettes	Your Kisses Are Wasted On Me	Memphis Industries/Cherrytree	2006	155
46	The Strokes	Juicebox	RCA	2006	155
47	Hooverphonic	Mad About You (Orchestra Version)	Columbia	2012	156
48	Nirvana	In Bloom	DGC	1991	156
49	The Van Jets	Ricochet	Belvédère	2005	156
50	Air	Surfing On a Rocket	Virgin	2004	157
51	Millencolin	No Cigar	Epitaph	2000	157
52	The Beach Boys	Surfin' USA	Capitol	1963	157
53	Shaggy	Boombastic	Virgin	1995	158
54	Jones & Stephenson	The First Rebirth (Original Mix)	Prolekult	1994	159
55	Kings of Leon	California Waiting	RCA/HandMeDown	2003	159
56	Michael Sembello	Maniac	Warner Bros	1983	159
57	OutKast	Hey Ya! (Radio Mix Club Mix)	LaFace	2003	159
58	Beyonce	Halo	Columbia	2008	160
59	Birdman & Lil Wayne	Stuntin' Like My Daddy (Street)	Cash Money/Universal	2006	160
60	Customs	Justine	Noisesome/EMI	2009	160

Table 4.1: List of all musical stimuli (Continued).

ID	Artist	Song	Label(s)	Year published	Tempo (BPM)
61	Mastodon	Spectrelight	Reprise/Roadrunner	2011	160
62	TNGHT	Higher Ground	Warp/LuckyMe	2012	160
63	P.O.D.	Alive	Atlantic	2001	161
64	Queens of the Stone Age	Little Sister	Interscope	2005	161
65	’T Hof Van Commerce	Baes (Radio Edit)	Plasticine	2012	162
66	Black Sabbath	Paranoid	Vertigo	1970	162
67	Blondie	One Way or Another	Chrysalis	1978	162
68	Karate	Ice or Ground	Southern	2002	162
69	Moby	Feeling So Real	Mute/Elektra	1995	162
70	Orchestral Manoeuvres In the Dark	Electricity	Factory	1979	162
71	U96	Love Religion (Video Edit)	Guppy/Motor	1995	162
72	Wham!	Wake Me Up Before You GoGo	Columbia	1984	162
73	Bomfunk MC’s	Freestyler	Sony Music Finland/Epidrome	1999	163
74	Jamaica	Cross the Fader	Downtown	2011	164
75	Midlake	Antiphon	Bella Union	2013	164
76	Muse	Survival	Helium 3/Warner Music Group	2012	164
77	Sugababes	About You Now	Island	2007	164
78	Ella Fitzgerald	A-Tisket, A-Tasket	Golden Options	2008	165
79	Ike & Tina Turner	River Deep Mountain High	Philes	1966	165
80	Green Day	Boulevard of Broken Dreams	Reprise	2004	166
81	Pixies	Where Is My Mind	4 AD	1988	166
82	Rammstein	Mann gegen Mann	Universal	2005	166
83	Arctic Monkeys	Do I Wanna Know	Domino	2013	170
84	Chet Faker	I’m Into You	Opulent/Remote Control	2012	170
85	Joy Division	Disorder	Factory	1979	170
86	Panic! At the Disco	I Write Sins Not Tragedies	Fueled by Ramen/Decaydance	2005	170
87	Queens of the Stone Age	No One Knows	Interscope	2002	170
88	The All-American Rejects	My Paper Heart	Doghouse/DreamWorks	2002	170
89	Foo Fighters	The Pretender	Roswell/RCA	2007	172
90	Netsky	Love Has Gone	Hospital	2012	172
91	Paramore	Misery Business	Fueled by Ramen	2007	172

Table 4.1: List of all musical stimuli (Continued).

ID	Artist	Song	Label(s)	Year published	Tempo (BPM)
92	The Streets	Fit But You Know It	Locked On/679	2004	172
93	DJ Fresh	Hot Right Now (Radio Edit)	Ministry of Sound	2012	174
94	Interpol	A Time To Be So Small	Matador	2004	174
95	Kanye West	Homecoming (feat. Chris Martin)	Roc-A-Fella/Def Jam	2008	174
96	Rudimental	Waiting All Night (feat. Ella Eyre)	Asylum	2013	174
97	Kelis & Andre 3000	Millionaire	Virgin	2004	176
98	Technohead	I Wanna Be a Hippy	Mokum	1995	177
99	Komatsu	Comin´	Lighttown Fidelity	2011	178
100	MoH́orizons	Pe Na Estrada (Radio Edit)	Agogo	2008	178
101	Tony Bennett & Lady Gaga	The Lady Is a Tramp	Sony Music Entertainment	2011	179
102	One Direction	Kiss You	Syco/Columbia	2012	180
103	Red Hot Chili Peppers	Can't Stop	Warner Music	2002	182
104	The Pointer Sisters	I'm So Excited	Planet	1982	184
105	Ok Go	Don't Ask Me	Capitol	2002	186
106	Joan Jett & The Blackhearts	I Love Rock 'N Roll	RAK	1975	188
107	Wheatus	Teenage Dirtbag	Columbia	2000	188
108	Absynthe Minded	Pretty Horny Flow	Abeille Musique	2008	190
109	Eminem	Berzerk	Aftermath Entertainment/Shady/Interscope	2013	190
110	Macklemore & Ryan Lewis	Thrift Shop (feat. Wanz)	Macklemore LLC/ADA	2012	190
111	Roxette	The Look	EMI	1988	190
112	Isbells	As Long As It Takes	Zeal	2009	197
113	Beyonce	Crazy In Love (feat. Jay-Z)	Columbia/Music World	2003	198
114	Rihanna	Pon de Replay	Def Jam	2005	198
115	Gorillaz	Stylo (Radio Edit) [feat. Mos Def & Bobby Womack]	Parlophone/Virgin	2010	200
116	Wallace Vanborn	Atom Juggler	PIAS	2010	200
117	Linkin Park	In the End	Warner Bros	2000	210

4.2.4 Apparatus

Participants were equipped with two iPods (fourth generation), one attached at each ankle. Using the Sensor Monitor Pro application on the iPods, data from accelerometers and gyroscopes was streamed wirelessly at 100 Hz to the main processing computer. A Wi-Fi hotspot (TP-Link N750) with special 3-dB gain antennas for longer range was used for maintaining a stable connection between the computer and sensors. Some minimal jitter and lag in the data stream were neutralized using a 500-ms buffer before processing.

Incoming sensor data was processed by a customized version of D-Jogger (Moens, Muller, van Noorden, Franěk, Celie, Boone, Bourgois, and Leman, 2014), a music alignment framework that selects and tempo-adapts music to runners' gait frequencies using kinematic sensor input. Music tempi were manipulated using a phase vocoder, which time stretches music without pitch modification. D-Jogger was adapted to match the experimental protocol (detect running cadence, playback tempo-matched music to this reference, increase or de- crease music tempo). The system logged all data and calculations in real time. Finally, the resulting auditory stimuli were sent back to the participant using a Sennheiser HDR130 audio transmitter (with a range of up to 100 m). The participant perceived the music through Sennheiser HD60 headphones connected to the transmitter (attached to the upper arm). The delay due to the wireless audio transmission was negligible.

4.2.5 Experimental procedure and set-up

The experiment took place in the Flanders Sports Arena of Ghent, Belgium. In order to select motivational music adapted to each runner's personal taste, participants performed the Brunel Music Rating Inventory 2 (BMRI-2) test (Karageorghis et al., 2006) at the start of the experiment. In this test, they were asked to rate all items of the music database by answering six questions about the motivational aspects of each song. Each item referred to an action, a time, a context, and a target (e.g. "The rhythm of this song would motivate me during a running exercise") (Ajzen and Fishbein, 1977). Participants responded on a seven-point Likert scale anchored by 1 ("strongly disagree") and 7 ("strongly agree"). Afterwards, participants filled out a questionnaire on personal background, music education, and sports training. At the same time, for each participant individually, the 20 songs that had obtained the highest scores during the BMRI-2 test were loaded into the D-Jogger system.

Subsequently, participants were equipped with the iPods, the wireless headphone, and the audio transmitter. Each participant was asked to run on a 200-m running track for four laps continuously, for 12 times. Participants were instructed to run at their own comfortable tempo. No information was distributed concerning the real purpose of the experiment, and all participants ran in solo conditions. After each set of four laps, a break of approximately 5 min was introduced to enable the participant to recover sufficiently. Meanwhile, they were asked to indicate how heavy the effort had been during the exercise. This was rated on a Rating of Perceived Exertion (RPE) Scale (Borg, 1998), ranging from 6 (“no exertion at all”) to 20 (“maximal exertion”).

To get acquainted with the experimental set-up, the first set of four laps consisted of a practice set during which no music was played. Each of the 11 following four-lap sequences consisted of (1) a lap without music, (2) a lap with tempo-matched music, and (3) two laps with tempo-changed music. In the first lap, the participant ran at his/her self-paced cadence without musical accompaniment. In the second lap, music with a tempo matching the cadence assessed during the final 20 s of the previous lap was played. The musical stimulus consisted of the song that obtained the highest score during the BMRI-2 test with a tempo that differed maximally 5% from the running cadence of the participant. After the song was selected, its tempo was adjusted to exactly match the mean running cadence. Finally, during the third and fourth laps, the tempo of the music was adjusted according to one of the 11 tempo-changed conditions.

In each of the 11 four-lap sequences, a different condition was tested. During the two final laps with tempo-changed music, the music tempo was adjusted to either -3.00, -2.50, -2.00, -1.50, -1.00, 0.00, +1.00, +1.50, +2.00, +2.50, or +3.00% of its original one, played during the second lap. This range was chosen since an average person can distinguish tempo variations from about 4% (Levitin, 2006) and since the aim of this study was to test spontaneous or unintentional entrainment. The different conditions were randomized over the experiment in such a way that each participant performed all conditions but no participants performed the conditions in the same order. To ensure that they were not aware of the actual objective, participants filled out a questionnaire regarding their perception of the purpose of the experiment at the end. Responses did not indicate that they were aware of the experiment’s real purpose.

4.2.6 Data analysis

4.2.6.1 Cadence adaptation

Running cadence was calculated using the iPods’ acceleration data. In order to check the degree of cadence increase/decrease, running cadence (SPM) recorded during the laps with tempo-changed music (*tempo-changed laps* or TCL) was compared to the cadence captured during the lap with tempo-matched music (*tempo-matched lap* or TML) and will be further referred to as *cadence adaptation*. As the tempo was gradually shifting during that period, the first 5 s of the laps with tempo-changed music was discarded. The final 20 s of those laps was also ignored as participants possibly altered their running behaviour due to the anticipated ending of the final lap (e.g. slowing down or speeding up).

$$\text{Cadence adaptation (\%)} \; = \frac{\text{avg(SPM\_TCL)}}{\text{avg(SPM\_TML)}} \tag{4.1}$$

4.2.6.2 Entrainment

A second measure of interest concerned the percentage of tempo-entrained steps during the laps with tempo-changed music. A step taken in a tempo sufficiently close to the music tempo (max. 1 % difference between SPM and BPM) at that specific moment is regarded as a tempo-entrained step. The tempo entrainment score is the percentage of tempo-entrained steps of the total amount of steps.

4.3 Results

4.3.1 Running cadence

This study tested whether the changes in music tempo would affect running cadence. A Kolmogorov-Smirnov test (KS test) showed that the assumption of normality was met, $D(161) = 0.04$, $p > .05$. A 11 × 2 × 2 repeated measures ANOVA with tempo condition as within-subject factor and gender and musical training as between-subject factors revealed a significant main effect of condition on cadence adaptation, $F(10, 40) = 6.50$, $p < .001$. Contrasts revealed a linear relation between condition and cadence adaptation, $F(1, 4) = 94.56$, $p < .001$, $r^2 = .96$. The evolution of cadence adaptation over the different conditions is shown in Figure 4.1.

There was no significant effect of gender, indicating rather similar levels of cadence adaptation for males and females, $F(1, 4) = 6.51$, $p = .06$, $r^2 = .62$. However, there was a significant interaction effect between tempo condition and gender, $F(10, 40) = 3.40$, $p < .01$. As can be seen in Figure 4.2, although for both males and females running cadence increased (or decreased) with increases (or decreases) in music tempo, these adjustments were more pronounced for women than for men. In addition, there was no significant effect of musical training, $F(1, 4) = 6.48$, $p = .06$, $r^2 = .62$, which indicated that participants without musical training displayed similar levels of cadence adaptation as participants with a musical background. Finally, no significant interaction effect was found between musical training and tempo condition, $F(10, 40) = 1.79$, $p = .10$ (see Figure 4.3).

4.3.2 Entrainment basin

In order to trace a possible basin for entrainment, the effect of the conditions on the level of tempo entrainment was tested. KS tests showed that the entrainment values were significantly non-normal, $D(161) = 0.15$, $p < .001$. Friedman's ANOVA

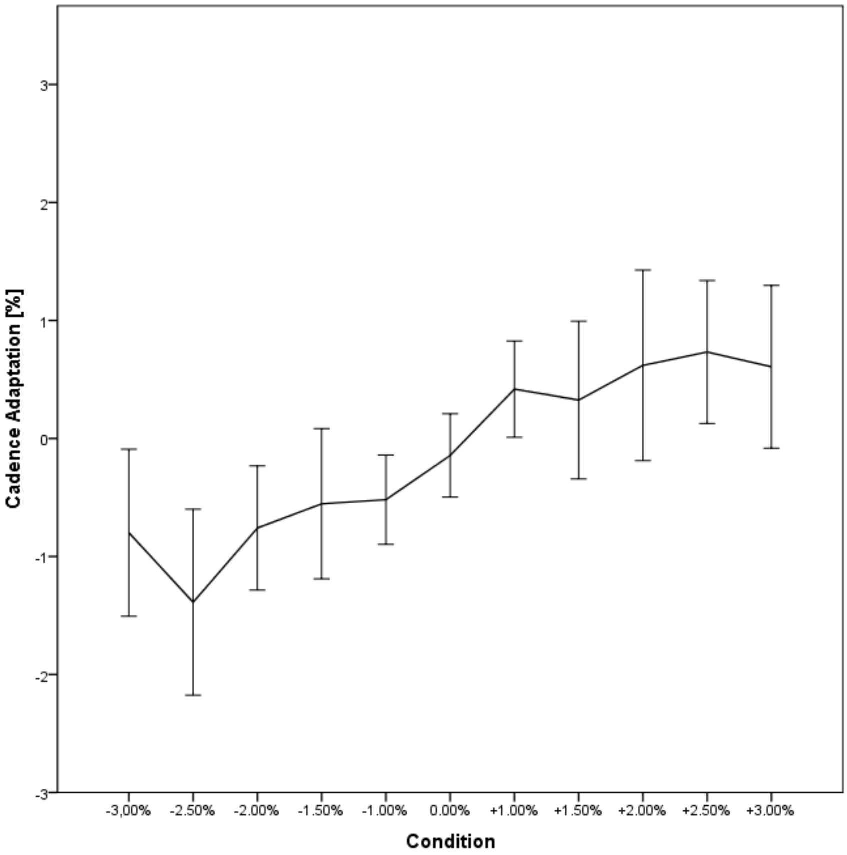


Figure 4.1: Mean tempo and cadence adaptation for the different conditions. Data presented is mean ± SE.

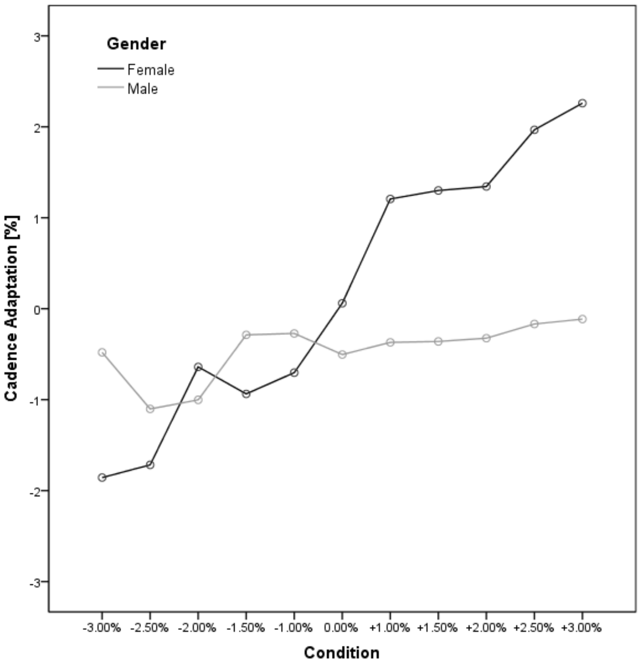


Figure 4.2: Interaction plot of estimated marginal means calculated for cadence adaptation at both gender levels.

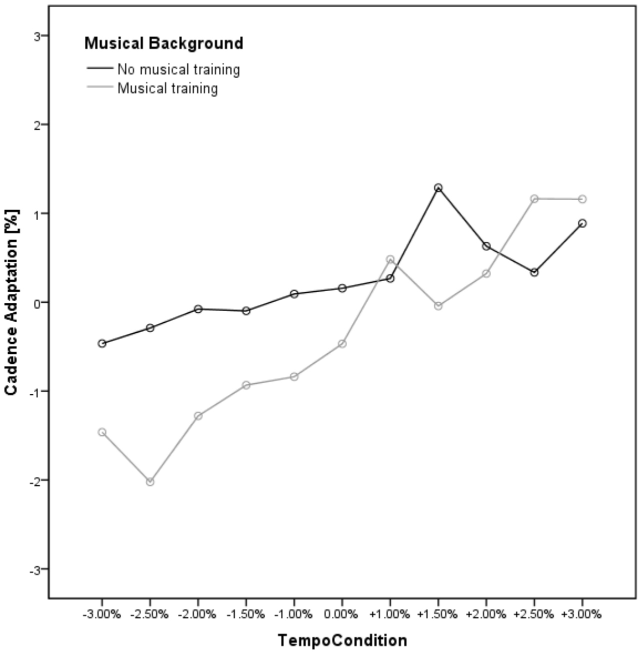


Figure 4.3: Interaction plot of estimated marginal means calculated for cadence adaptation at both musical background levels.

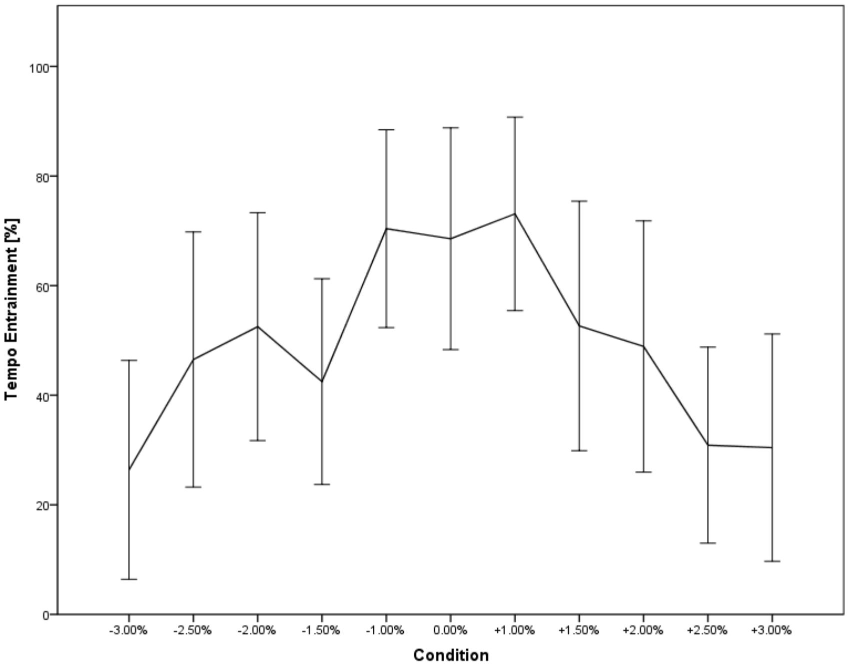


Figure 4.4: Entrainment basin displaying mean tempo entrainment for the different conditions. Data presented is mean ± SE.

showed a significant effect of condition on tempo entrainment, $\chi^2(10) = 19.27$, $p <$ .05. Wilcoxon tests were used to follow up this finding, and all conditions were compared against the control condition (0% of tempo change). A Bonferroni correction was applied, and all effects are thus reported at a .005 level of significance. It appeared that, compared to the control condition (Median (*Mdn*) = 74.25), tempo entrainment was significantly lower in the +2.50% condition ((*Mdn* = 12.48), Z = -2.92, r^2 = .53) and tended to be lower in the +3.00% ((*Mdn* = 14.01), Z = -2.41, p = .016, r^2 = .36) and -3.00% conditions ((*Mdn* = 6.97), Z = -2.48, p = .013, r^2 = .38). Figure 4.4 represents the mean tempo entrainment for every single condition.

It is noteworthy that the entrainment basin did not differ significantly between females and males (see Figure 4.5). However, the mean level of entrainment appeared to be higher for females as compared to their male counterparts. When testing this assumption, a Mann-Whitney test indeed revealed significantly higher levels of tempo entrainment for female participants (*Mdn* = 60.05) compared to their male counterparts (*Mdn* = 39.10), U = 10.00, Z = -2.28, $p < .05$, r^2 = .32. It was also tested whether a link between musical training and entrainment could be found. However, no significant difference was found between participants with

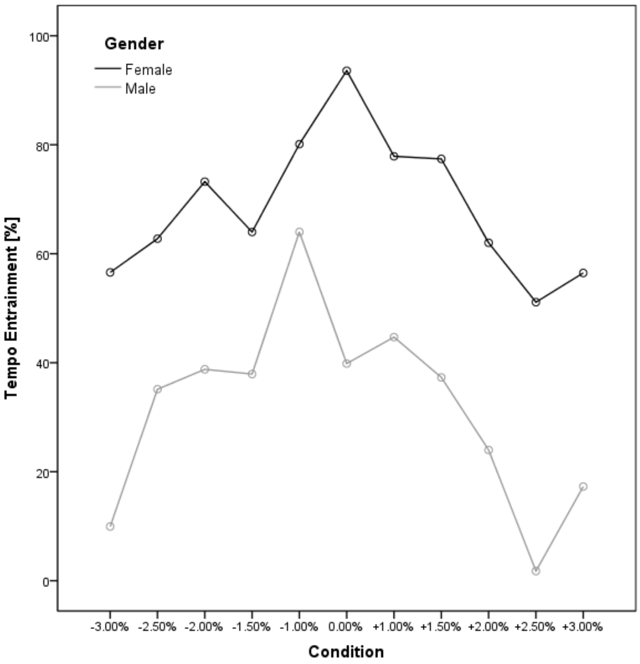


Figure 4.5: Interaction plot of estimated marginal means calculated for tempo entrainment at both gender levels.

(*Mdn* = 50.73) or without musical background (*Mdn* = 38.24) regarding their level of entrainment, U = 18.00, Z = -1.30, p = .19, r^2 = .11.

4.3.3 Perceived exertion

It was also checked whether the level of entrainment could be related to the degree of perceived exertion. For this purpose, a two-tailed Spearman's correlation test was performed on entrainment values and ratings on the RPE scale. However, no significant relationship between perceived exertion and entrainment was found, r_s = -.04, p = .58.

4.4 Discussion

The aim of this study was to examine whether music tempo could serve as a means to influence running cadence. Results indeed unveiled a significant relationship between imperceptible alterations in music tempo, in proportion to recreational runners' self-paced running cadence, and cadence adaptation. In other words, faster music resulted in an increase, while slower music led to a decrease in running cadence. This effect can be explained through the idea of a sensorimotor mechanism that aligns footfall to musical beats. Adjustment of the footfalls to the beats relies on a phase-error correction mechanism of expected sensory outcomes (Repp and Su, 2013). Consequently, our study confirms results of previous research stressing the effect of music tempo on exercise performance (Edworthy and Waring, 2006; Priest et al., 2004; Waterhouse et al., 2010; Karageorghis et al., 2006; Mendonça et al., 2014). This particular study also extends preceding research, as in this case, the effect on running cadence was tested using imperceptible changes in musical tempi with no explicit instructions regarding entrainment with the music. In contrast, in past research, participants were generally instructed to couple movement to music. Even if this was not the case, employed tempo variations usually proved to be too large to be unnoticeable. For example, Waterhouse et al. (2010) compared cycling performance to normal, fast (increase of 10%), and slow music (decrease of 10%). Edworthy and Waring (2006) examined treadmill-running behaviour when listening to music with a tempo of either 200 or 70 BPM, while Karageorghis et al. (2006) employed tempi of 80, 120, and 140 BPM in their study on walking. In contrast, a maximum deviation of 3% from the original music tempo was implemented in this particular study, as the amount of variation in tempo that an average person can distinguish is situated around 4% (Levitin, 2006). Consequently, novel insights were presented in this study, as it was shown that recreational runners are able to adapt their running cadence (up to 2% of the original cadence) to tempo changes in music (up to 3% of the original tempo) without being aware of this attunement and without being instructed to do so. This finding supports the notion that an individual tends to synchronize spontaneously to an auditory rhythm occurring in the environment (Lopresti-Goodman et al., 2008; Schmidt et al., 2007; Repp and Su, 2013) and is in agreement with the natural predisposition of humans to respond to rhythmical qualities of music (Karageorghis et al., 1999; Large, 2000).

It was also tested whether a basin for spontaneous entrainment of running cadence to music tempo could be found. Previous research has suggested that a range of period differences exists over which entrainment of movements of an individual with an environmental rhythm generally occurs and that beyond this range the occurrence of unintentional coordination is highly unlikely (Richardson et al., 2005; Von Holst, 1973; Lopresti-Goodman et al., 2008; Schmidt and Richardson, 2008; Schmidt et al., 2007; Strogatz, 1994). Results indeed revealed a significant decrease in the level of entrainment in combination with increasing deviations from the original music tempo. The degree of entrainment with the tempo of the music dropped significantly as soon as tempo increases of 2.50% were introduced but also tended to drop at decreases of 3.00%. This could be explained by the fact that when deviations (especially increases) from the original, self-selected, and thus comfortable running tempo got larger, the effort required from the runner increased and at a certain point probably required too much effort, resulting in significantly lower levels of entrainment. As such, our results are in line with the idea of an entrainment basin for spontaneous coordination (Richardson et al., 2005; Von Holst, 1973; Lopresti-Goodman et al., 2008; Schmidt and Richardson, 2008; Schmidt et al., 2007; Strogatz, 1994). However, our findings also contrast with those of Mendonça, Oliveira, Fontes, and Santos (2014), showing that for uninstructed synchronization of walking to music, participants did not adapt their step frequency to music that differed 5 to 10% above and under their nominal step frequency, while they did adjust when synchronization was instructed. This could imply that a wider basin might be found for instructed entrainment to music tempo, while spontaneous entrainment occurs only when smaller deviations from the original tempo are introduced. But this is subject to some speculation and might benefit from further research.

Music is believed to only successfully distract from fatigue and discomfort when physiological awareness and perceived exertion are relatively low (Rejeski, 1985; Nethery, 2002; Tenenbaum, 2005; Razon et al., 2009; Hutchinson and Tenenbaum, 2007). Therefore, in order to control for possible effects of perceived exertion, after each set of four laps, a break of approximately 5 min was introduced. Besides, the relationship between the degree of perceived exertion and the level of entrainment was also examined in the analysis. Nevertheless, no significant relationship between perceived exertion and entrainment was found. This could be due to the fact that, in general, participants did not perceive the task as extremely light or exceptionally hard but mostly rated their perceived exertion as intermediate. A reason for this might be that runners ran at their comfort tempo and no large shifts in the tempo of the music were incorporated in the study, but it might also be partly due to the introduction of the breaks after each condition. Besides, most previous research demonstrating decreasing levels of influence of music on attentional processes at higher exercise intensities tested this effect using asynchronous music, (e.g. Rejeski, 1985; Nethery, 2002; Tenenbaum, 2005; Razon et al., 2009; Hutchinson and Tenenbaum, 2007). Whether this also applies to synchronous music still remains rather unclear, although, in their study on the effect of synchronous music on treadmill running, Terry et al. (2012) did indicate lower levels of perceived exertion, assessed at moderate-to-high work intensities, for synchronous music compared to the no-music control. Yet, the magnitude of the differences in rating of perceived exertion proved to be rather small.

Another hypothesis referred to gender. We expected female participants to exhibit larger levels of entrainment in comparison with their male counterparts. Indeed, significantly higher levels of tempo entrainment were observed for females. In addition, although the effect of the music tempo on running cadence was unveiled for both males and females, changes in running cadence as a result of deviations in music tempi were more pronounced for female runners than for male ones, which suggests that women were more influenced by tempo changes than men. These findings resonate with the general belief that women are more responsive to musical stimuli (Priest et al., 2004; Waterhouse et al., 2010; Karageorghis et al., 1999; Pellett, 1994).

One should bear in mind that the current study focused on self-paced running, and thus, the type of exercise under study concerned one that is of low-to-moderate intensity. When studying activities with higher levels of intensity, music might not have a comparable effect on the exercisers' performance, as when high workloads are undertaken, the exerciser's attention could be shifted towards the painful or fatiguing effects of the exercise (Rejeski, 1985; Nethery, 2002; Tenenbaum, 2005; Razon et al., 2009; Hutchinson and Tenenbaum, 2007). However, although most previous research on high-intensity exercise did not show any remarkable effects of music tempo, exemplary studies that have unveiled such effects do exist as well. In a study by Rendi, Szabo, and Szabó (2008), for example, where exercisers were asked to perform a 500-m rowing sprint, in which physiological awareness is high, it was shown that fast-tempo music increased arousal and, in turn, performance, even during high-intensity sprints, while music with a slow tempo did not generate such stimulating effects. Further exploration of the impact of music tempo on sport activities with high workloads would be beneficial.

It could also be questioned whether spontaneous, thus uninstructed, entrainment is generally more beneficial with regard to exercise performance than instructed entrainment. It could be suggested that when synchronization is spontaneous, it may require less attentional resources, thus leading to even more important benefits (e.g. leaving free attentional resources to realize other tasks). Besides, exercise training could be simplified when instruction would prove to be redundant. On the other hand, it has been indicated that instructed synchronization is a form of active attentional manipulation, which has been shown to have more positive effects, at least in the form of perceived exertion and exercise efficiency (Lim et al., 2014; Karageorghis et al., 2009). However, as this question has not been solved yet, the discussion whether spontaneous synchronization is more beneficial compared to instructed (or even imposed) synchronization should be unravelled in future studies.

In this particular study, recreational runners were tested. However, since music is believed to be more beneficial for recreational compared to trained exercisers (Karageorghis and Priest, 2012b), different results might have been obtained if competitive runners were tested. Previous research on treadmill running indicated that less trained exercisers might depend to a greater extent on the positive feeling states generated by music, while trained exercisers generally tend to focus on the tasks and specifics of their training (Brownley et al., 1995; Mohammadzadeh et al., 2008). Furthermore, as (either recreational or professional) runners do not typically tend to run distances of 800 m consecutively, interrupted by short brakes, it might be interesting to investigate whether the effect of music tempo is sustained over the course of longer, interrupted distances. Whether the entrainment basin for recreational runners would differ from that of professional runners and whether its effects are sustained over longer distances could be tested in future research.

4.5 Conclusions

To conclude, it was unveiled that music tempo could serve as an unprompted means to re(shape) running cadence of recreational runners. This influence was shown to have a certain range, which suggests that maximal effects of music tempo can only be obtained up to a certain level of tempo change and proved to be stronger for female compared to male runners. As modifying step rate may prove beneficial in the prevention and treatment of common running-related injuries, this novel finding could be especially relevant for treatment purposes, such as exercise prescription and gait retraining.

My main contribution is: co-development of experimental design, co-execution of experiment, main analysis of the data, and writing the paper.

5

Shifting the Musical Beat to Influence Running Cadence

Buhmann, J., B. Moens, V. Lorenzoni, and M. Leman

In E. Van Dyck (Eds.), *Proceedings of the 25th Anniversary Conference of the European Society for the Cognitive Sciences of Music (ESCOM)*, Ghent, Belgium.

Abstract

The use of music in the fields of sport and rehabilitation has been explored in several ways. Mostly, these studies have dealt with the effect of different types or genres of music and the difference between using synchronous or asynchronous music. Within the studies on synchronous music there is some discrepancy as to what is considered to be synchronous. This varies from music with a tempo in the range of the tempo belonging to a certain task, to music that is exactly matched in tempo to the task's tempo. The use of tempo-matching music allows us to even do more fine-grained music alterations: shifting the beat to try to spontaneously manipulate a runner's cadence. Musical tempo has been shown to have an effect on running. Instead of changing running cadence by manipulating the musical *tempo, we explored the possibility of manipulating cadence by changing the relative phase angle of the musical beat. Twenty-six recreational runners ran four minutes, nine times. The first minute of each 4-min sequence consisted of running without musical accompaniment. Running cadence was measured and the average cadence of the final 15 sec was used to select a musical track with matching tempo. In the following three minutes we tried to increase or decrease the runner's tempo up to 5%. Three different coupling strengths, meaning a small, medium or big timing difference between the beat and the footfall, were tested. The study revealed a significant main effect of the phase angle adjustment strategies on runners' cadence and velocity. Furthermore, a significant gender interaction effect was found for runners' cadence adaptation. Women spontaneously increased or decreased their running tempo with the +5% and -5% target tempo conditions respectively. Men, however, could be sped-up, but not slowed-down more than the decrease in cadence that was already observed when the musical beats were perfectly synchronized with the footfalls. In addition to effects on kinematics, the results showed higher enjoyment levels with music than with metronome, and a decrease in enjoyment with the -5% tempo conditions. Being able to influence runners' cadence, velocity, and enjoyment through phase-shifted music is an interesting finding in the light of preventing and treating common running-related injuries.*

5.1 Introduction

The use of rhythmic auditory stimulation (RAS) has been given a lot of attention in light of influencing cadence in running and cycling and in gait rehabilitation programs for e.g. patients with Parkinson's disease. Metronome sequences as well as music (with clear beats) can be applied for RAS. The main influencers of gait with metronomes are the sound and the frequency of the clicks. For music, however, not only the sound and frequency of the beats are important. Other music-inherent qualities at micro-level (inter-beat period) and macro-level (over the course of several beat periods) can influence people's walking or running cadence, as well as their motivation (Buhmann, Desmet, Moens, Van Dyck, and Leman, 2016; Leman, Moelants, Varewyck, Styns, van Noorden, and Martens, 2013)

Within sports and gait rehabilitation the tempo (cadence) and strength (e.g. step size) of movement are important variables for improving performance or preventing injuries. According to a review study by van Gent et al. (2007) running may cause injuries, especially to the lower extremities, ranging from 20-79% of incidences for non-elite runners. The knee is the predominant site for this type of injuries that are typically caused by overstriding. Therefore, a popular strategy for preventing knee injuries is to reduce step size by increasing running cadence (Heiderscheit, Chumanov, Michalski, Wille, and Ryan, 2011).

Music is pre-eminently adequate to guide or spontaneously influence a person's running cadence while being motivating as well. A study by Van Dyck, Moens, Buhmann, Demey, Coorevits, Bella, and Leman (2015) revealed the possibility to spontaneously affect running cadence by deviating the tempo of the music from runners' individual preferred cadence. Tempo manipulations within 2.5% of a runner's cadence were found to be effective. Larger deviations from runners' cadence were not or less effective. A music-to-movement alignment strategy that continuously manipulates the musical tempo only affects the time between subsequent beats. Such a strategy does not take into account the specific moments when the beats occur, or how these time instants relate to the instants of the footfalls. In other words, the relative phase angle between beat and step is disregarded. An alignment strategy that is able to consider relative phase angles might be better suited to keep the synchronization level high and to spontaneously manipulate runner's cadence. In this study several variations of such relative phase alignment strategies are tested and compared.

Our hypothesis is that when people run in synchrony with a musical beat and the music is then manipulated in such a way that the beat is placed prior to the moment of the footfall (i.e. positive relative phase angle), the runner will try to re-establish synchronization (a zero relative phase angle) by speeding up (cadence and speed). On the contrary, we hypothesize that manipulating the beat to come after the moment of the footfall will result in slowing down cadence and speed to re-establish running in synchrony with the music. In this study we tested this hypothesis by trying to manipulate runners' cadence towards +5% and -5% of their measured preferred cadence. This was explored at three interesting 'levels' of relative phase angle manipulation:

- **Subconscious or subliminal**: a subtle phase shift up to a maximum of +/-25° that is not perceivable by the participant.
- **Barely noticeable**: a maximum phase shift of +/-50° that is most likely not perceivable by the participant.
- **Conscious**: a maximum phase shift of +/-75° that is most likely to be noticed by the participant. A relative phase angle of this size could be perceived as annoying by some runners.

5.2 Methods

5.2.1 Participants

In total, 26 healthy, adult participants (12 males) took part in the study. All participants were recreational runners (M_{age} = 22.81 years; SD_{age} = 3.25 years) and indicated to be capable of running 30 minutes continuously. The study was approved by the Ethics Committee of the Faculty of Arts and Philosophy of Ghent University and was in accordance with the statements of the Declaration of Helsinki.

5.2.2 Experimental design

5.2.2.1 Stimuli

The natural running cadence for recreational runners lies somewhere between 130 and 200 steps per minute (SPM). We therefore selected musical tracks within this tempo range in four different genres: pop, rock, dance, and classics. This gave participants the opportunity to run with music they would normally choose to listen to. Using the Essentia Beat Tracker (Bogdanov, Wack, Gómez, Gulati, Herrera, Mayor, Roma, Salamon, Zapata, Serra, et al., 2013) all beat instants were extracted and hence the number of beats per minute (BPM). After that, BeatRoot (Dixon, 2007), a beat-tracker with a graphical user interface, was applied to double-check the beats of each track and alter beats not picked up correctly by the software if needed. Using MatLab the stability of the track's tempo was checked. Every track with a standard deviation from the mean BPM of more than two was excluded. We also excluded tracks that were shorter than 3 min 30 s, as each tested condition had to last at least three minutes, and an increase in original tempo could shorten the duration of a track. In total 112 tracks were selected: pop (26), rock (31), dance (33) and classics (22). Furthermore, we made sure the tracks were uniformly spread over the database in terms of BPM, so every BPM category was adequately represented. This was achieved by dividing the tempo range in sub ranges, each representing at least five tracks.

5.2.2.2 Apparatus

In order to have a mobile data collection system, participants were equipped with a backpack holding a 7" tablet (Panasonic FZ-M1) running Windows 8.1. They were also equipped with two (fourth generation) iPods, one on each ankle, and a Wi-Fi router (TP-Link M5360) that ensured a reliable communication between all crucial components. Using the Sensor Monitor Pro application on the iPods, data from accelerometers and gyroscopes was streamed wirelessly to the tablet at a sampling rate of 100 Hz, enabling the detection of footfall instants. Speed measurements were performed using a sonar system (MaxBotix LV-MaxSonar-EZ: MB1010) mounted on the backpack and connected to the tablet through a Teensy 3.1 micro-controller. It detected regularly placed marker rods around the running track of 1.90 m high. The time it took to cover each 10 m interval was used to compute the absolute speed of the runner. The analogue signal was sampled at 30 Hz and digitized using the Teensy. The software on the tablet computed the running tempo from the detected footfall instants, which was used as a basis for defining the tempo of the selected music. The relative phase of the moment of the musical beat compared to the moment of the footfall was adapted based on the selected alignment strategy (see Table 5.1). Finally, the manipulated music was sent back to the participant using Sennheiser HD60 headphones connected to the tablet.

5.2.2.3 Procedure

All experiments took place in the Flanders Sports Arena of Ghent, Belgium. After a 4-minute warm-up to get to know the running track participants were equipped, and asked to run on the 200 m running track for four minutes continuously, and this for eight consecutive times. They had to select at least two of the four genres where the software could select music from. Each 4-minute condition started with one minute running in silence, after which a metronome sequence or a musical track was started. The first run was the isochronous metronome condition in which the music tempo was matched to the runner's preferred cadence. In each of the following seven 4-minute runs, a different music alignment strategy was tested (Table 5.1) and it was ensured that all orders could occur only once. Participants were instructed to run at their own preferred tempo (f_{pref}). No information was distributed concerning the real purpose of the experiment, and all participants ran in solo conditions. After each run, the participants were instructed to fill out a

Strategy	**Type of auditory adaptation**
+5%_LPAA	Low relative phase angle adjustment of music (approx. 25°) until +5% of f_{pref} is reached.
+5%_MPAA	Medium relative phase angle adjustment of music (approx. 50°) until +5% of f_{pref} is reached.
+5%_HPAA	High relative phase angle adjustment of music (approx. 70°) until +5% of f_{pref} is reached.
-5%_LPAA	Low relative phase angle adjustment of music (approx. -25°) until -5% of f_{pref} is reached.
-5%_MPAA	Medium relative phase angle adjustment of music (approx. -50°) until -5% of f_{pref} is reached.
-5%_HPAA	High relative phase angle adjustment of music (approx. -70°) until -5% of f_{pref} is reached.
Music control	Relative phase angle adjustment at 0°: musical beats continuously match steps at runner's f_{pref}.
Metronome	Isochronous metronome sequence where the tempo matches the initially measured f_{pref}.

Table 5.1: Descriptions of all the tested audio-to-movement strategies: low (L), medium (M), or high (H) phase angle adjustments (PAA) to manipulate runners' preferred cadence (f_{pref}) or not (Metronome and Music control).

questionnaire, and recover before starting the next condition. The first part of the questionnaire related to the perceived amount of exertion (RPE) indicated on the Borg Scale (Borg, 1998). The second part related to the motivational aspects of the musical tracks they heard while running (Brunel Music Rating Inventory 2 (BMRI 2) by Karageorghis, Priest, Terry, Chatzisarantis, and Lane (2006)). Participants were also asked if they knew the track they had just heard. The third part of the questionnaire related to the physical enjoyment. This was indicated on the 8 item version of the Physical Activity Enjoyment Scale (PACES) (Kendzierski and DeCarlo, 1991; Mullen, Olson, Phillips, Szabo, Wójcicki, Mailey, Gothe, Fanning, Kramer, and McAuley, 2011), a single factor scale to assess the level of enjoyment during physical activity in adults across exercise modalities. Afterwards, the participants filled out the last part of the questionnaire on personal background, music education and sports training.

5.2.3 Cadence and speed measurements

We examined the effect of the different alignment strategies on kinematic parameters such as cadence and speed. Average cadence and speed values during music playback (2:30 3:30) are compared to those in the preceding silence (0:45 1:00). The resulting dependent variables are reflected as percentages, where zero indicates no difference, while a negative or positive value indicates a respective decrease or increase in cadence or speed compared to the initial silent part of the condition.

5.2.4 Data analysis

All six phase angle adjustment (PAA) strategies were compared to the music control. A 2x7 mixed-design ANOVA test with gender (male, female) as between-subjects variable and alignment strategy as within-subjects variable was performed for change in cadence and speed. For motivational scores (PACES) Wilcoxon signed-rank tests were performed comparing all PAA strategies with the music control, average -5% and +5% with the music control, and all music conditions with the metronome condition.

5.3 Results

5.3.1 Cadence

A 2x7 mixed-design ANOVA test with gender (male, female) as between-subjects variable and alignment strategy as within-subjects variable revealed a significant main effect of the strategy on the change in cadence from silence to music, $F(6, 72) = 13.23$, $p < .001$. Contrasts revealed that for all speeding up conditions – (+5%_LPAA) $F(1, 12) = 12.99$, $p = .004$, $r = .72$, (+5%_MPAA) $F(1, 12) = 8.76$, $p = .012$, $r = .65$, (+5%_HPAA) $F(1, 12) = 8.57$, $p = .013$, $r = .65$ – cadence changes were significantly higher ($M = 0.53\%$, $SE = 0.52$, $M = 0.52\%$, $SE = 0.33$, and $M = 0.54\%$, $SE = 0.47$ respectively), than the music control ($M = -0.80\%$, $SE = 0.52$). Also, -5%_LPAA results in significantly lower tempo ($M = 1.86\%$, $SE = 0.27$) than the music control, $F(1, 12) = 11.47$, $p = .005$, $r = .70$.

There was no significant main effect of gender, indicating that on average there were no significant differences in change in cadence between male ($M = -0.96\%$, $SE = 0.41$) and female participants ($M = -0.16\%$, $SE = 0.40$), $F(1, 12) = 1.94$, $p = .19$, $r = .37$.

Nevertheless, a significant gender interaction effect was observed, $F(6, 72) = 3.19$, $p = .008$, indicating that for men and women changes in cadence varied between strategies. Contrasts were performed, revealing interaction effects between gender and all -5% conditions: gender x -5%_LPAA x music control, $F(1, 12) = 15.14$, $p = .002$, $r = .75$, gender x -5%_MPAA x music control, $F(1, 12) = 8.73$, $p = .012$, $r = .65$, and gender x -5%_HPAA x music control, $F(1, 12) = 5.11$, $p = .043$, $r = .55$. Figure 5.1 shows the cadence change for the different strategies and genders. Compared to the music control, both males and females increase cadence in the +5% conditions, but only females slow down their cadence in the -5% conditions. For men, the -5% conditions have no effect compared to the music control.

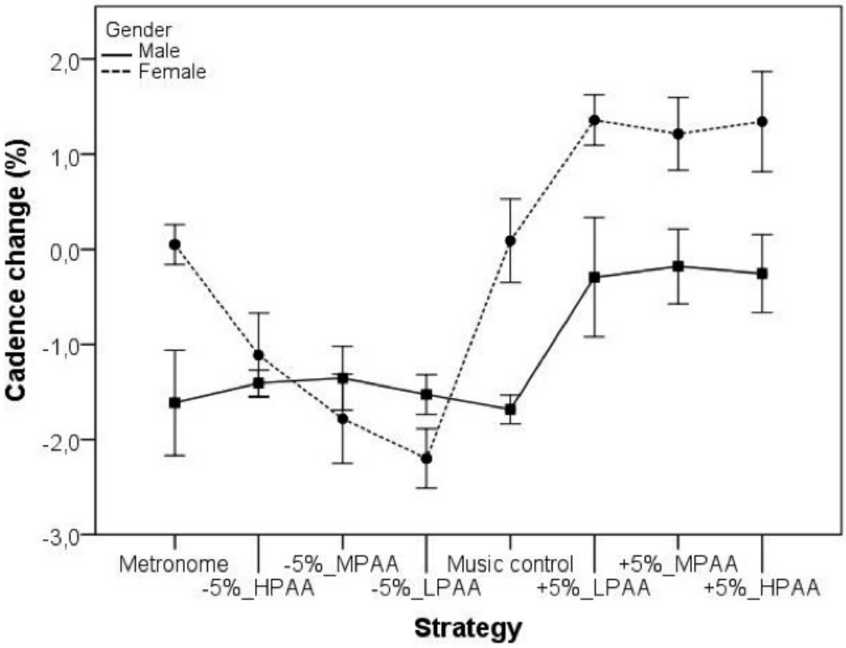


Figure 5.1: Mean cadence change (% of music vs. silence) and SEs for men and women per audio-to-movement alignment strategy.

Comparisons (*Mdn*)			***T***	***p***	***r***
Metronome (37.06)	x	+5%_LPAA (72.63)	2	< .001	-.61
		+5%_MPAA (69.38)	2	< .001	-.61
		+5%_HPAA (65.63)	22	< .001	-.53
		-5%_LPAA (60.75)	18	.002	-.50
		-5%_MPAA (66.88)	3	< .001	-.60
		-5%_HPAA (57.56)	9	< .001	-.58
		Music control (67.13)	0	< .001	-.62
-5% (58.83)	x	Music control (67.13)	52	.009	-.39

Table 5.2: Significant differences in enjoyment ratings (PACES): Wilcoxon signed-rank tests comparing metronome with music conditions, and -5% conditions with the music control.

5.3.2 Speed

All PAA strategies were compared with the music control. A significant main effect of the strategy on the change in speed was observed, *F*(6, 72) = 2.36, *p* = .039. Contrasts revealed that for +5%_LPAA, *F*(1, 12) = 10.30, *p* = .008, *r* = .68, the speed change was significantly higher (*M* = 3.97%, *SE* = 1.41) than for the music control (*M* = -1.08%, *SE* = 1.45). There was no significant main effect of gender, *F*(1, 12) = 2.44, *p* = .144, *r* = .41, and also no interaction effect between strategy and gender, *F*(6, 72) < 1, *p* = .43.

5.3.3 Enjoyment

Wilcoxon signed-rank tests (comparing all PAA strategies with the music control) were performed on the scores of the PACES test. No effect on ratings of physical enjoyment was observed. We were also interested to see if enjoyment ratings would differ when people were spontaneously sped-up or slowed-down. Therefore, we compared average PACES ratings for the three +5% and the three -5% conditions with the music control. After Bonferroni corrections (significance level at 0.025) Wilcoxon signed-rank test showed no difference, *T* = 145, *p* = .63, *r* = -.07, in ratings for the +5% conditions (*Mdn* = 64.66) and the music control (*Mdn* = 67.13). Nevertheless, the -5% conditions were rated significantly lower (*Mdn* = 58.83) than the music control, *T* = 52, *p* = .009, *r* = -.39.

In addition, compared to the metronome condition all music conditions were rated significantly more motivating (significance level at 0.007 after Bonferroni corrections). See Table 5.2 for the results of the Wilcoxon signed-rank tests.

5.4 Discussion

This study showed the possibility to spontaneously increase or decrease a runner's cadence with music-to-movement alignment strategies that manipulate the relative phase between the moments of the musical beats and the footfalls. In addition a strategy x gender interaction effect was observed, indicating that although the speeding-up strategies were effective for men and women, only women responded with decreased cadence to the slowing-down strategies. Finally, no motivational differences were revealed between the different music-alignment strategies, although on average the slowing down strategies were enjoyed less than the music control strategy. Additionally, all of the music strategies were enjoyed more than the metronome condition.

5.4.1 Phase shifting effects on cadence and speed

For speeding-up all three phase angle adjustment levels resulted in higher cadence than the control condition. The largest effect size however, was observed for the strategy that manipulated the phase angle the least. This was also the only strategy that significantly increased speed. In addition, for slowing down only the strategy that induced the smallest relative phase angles proved to be effective in decreasing runner's cadence. It seems that manipulating the phase angle between the beat and the footfall on a subconscious level was most effective. On average a 25° positive or negative relative phase was continuously induced by the strategy to drive runners to a 5% higher or lower cadence than their initial preferred cadence. For a running cadence of 160 SPM this comes down to shifting the beat 26ms before or after the predicted moment of the footfall.

Although no changes in RPE were unveiled between the different PAA levels, we did observe higher levels of synchronization (resultant vector length) with the LPAA strategies ($M = 0.92$, $SE = 0.01$), than with the HPAA strategies ($M = 0.87$, $SE = 0.01$), $F(1, 21) = 9.23$, $p = .006$, $r = .55$. Being more in phase with the LPAA strategies means that the cadence-guiding capacity was more constant over the course of a 4-minute run. The HPAA strategies contained more out-of-phase, so no-cadence-guiding moments. The fact that small, subliminal changes in relative phase are most effective in manipulating cadence could be explained by the higher stability in cadence guiding.

5.4.2 Gender interaction effects

The hypothesized effects of the phase manipulation strategies proved to be true for the women in this study. For men, however, the effects were slightly different: although the speeding-up strategies were able to increase running cadence, the slowing-down strategies had no effect compared to the music control condition.

We can conclude from the music control condition that women tend to keep their cadence more or less stable throughout a 4-minute run: 0.09% cadence increase compared to the beginning of the run where no music was played. Nevertheless, on average the men tend to slow down -1.69% in the control condition. A possible explanation could be that male runners typically start somewhat faster and slow down their cadence over the course of time. Their tempo already being decreased makes it harder for the slowing-down strategies to have an additional effect. The speeding-up strategies resulted in higher running cadence compared to the control condition, but cadence was only increased up to the cadence level runners had at the start of the 4-minute run. In other words, for male runners the speeding-up conditions resulted in maintaining cadence (-0.29%) throughout the run.

According to Karageorghis, Terry, and Lane (1999) men pay less attention to the rhythmical characteristics of music than women do. This could explain that beat-shifting techniques as tested in this study are less effective for cadence manipulation in males than in females.

5.4.3 Enjoyment

Enjoyment ratings with the PACES scales proved to be higher for all seven of the music conditions compared to the metronome condition. This is in line with a study on cycling that showed more positive affective valence for music conditions (synchronous and asynchronous) compared to a metronome condition (Lim, Karageorghis, Romer, and Bishop, 2014).

When we compare all the music PAA conditions with the music control condition, enjoyment ratings are not significantly different. However, a difference was observed when the average ratings for the speeding-up conditions were compared with the average ratings for the slowing-down conditions. Compared to the music control no additional enjoyment of the speed-up strategies was observed, but for the slowing-down strategies a decrease in enjoyment level was observed. A study by Wellenkotter, Kernozek, Meardon, and Suchomel (2014) revealed that a 5% decrease in cadence is accompanied by increased contact time with the ground per foot strike and increased peak force and peak pressure on the heel. This increases the risk for running-related injuries, which might in turn decrease running comfort or enjoyment, as shown in our results.

5.5 Conclusion

With this study we were able to show that shifting musical beats influences runners' cadence, speed, and enjoyment. Playing the music in such a way that the beat comes slightly earlier than the footfall results in increased running cadence and speed. If the beats are played just after the footfalls, running cadence is decreased. We also demonstrated that this method is less effective for men: we only achieved a speed-up in tempo, but the slowing-down strategies had no additional slowing-down effect compared to the non-manipulated music condition.

Music being more motivating than a metronome is almost stating the obvious. Our results confirm this. It is, however, worth noting, since the use of a metronome is still common practice in running training (to achieve higher cadence) and gait rehabilitation. In addition to other studies, our results underline a benefit of music over a metronome.

Although the size of the relative phase angle adjustments had no effect on enjoyment, a significant decrease in enjoyment was observed when runners were slowed-down. This is in line with a higher impact caused by a decrease in cadence. Hence, trying to decrease cadence should be done with care if at all necessary.

Music-to-movement alignment techniques such as demonstrated can help preventing running-related injuries, and improve gait or running performance. In view of general health the use of motivating music contributes to improved adherence to training programs.

6
Discussion and Conclusions

6.1 Answering the research questions

The work in this thesis can be devided into two main research pillars, each with its own research questions. The paragraphs below describe the main and more specific research questions per topic.

6.1.1 Movement-to-music adjustments

One of the main points of interest in this thesis was to explore if and how different types of tempo-matching music could spontaneously influence self-paced walking velocity. This work is described in chapter 2, and the main research question we had was:

Can expressive features of music influence the velocity of self-paced walking, spontaneously?

An earlier study by Leman et al. (2013) showed the effect of expressive musical features on step length when being instructed to walk at a tempo of 130 BPM. With the study in chapter 2 we were able to reproduce these results (be it with a smaller effect size) for walking at a self-paced comfortable tempo, without being instructed to synchronize with the tempo-matching music. The answer is therefore positive: some types of music can spontaneously increase walking velocity, whereas other types of music can have a decreasing effect on self-paced walking velocity.

The following two more specific research questions were also answered:

- **Is the velocity of self-paced walking influenced by phase-coherence?**
  The results demonstrate that music with velocity-increasing qualities affects people that synchronize their step frequency with the musical tempo as well as people that do not walk in phase coherence with the musical beat. However, the effect size when walking in phase coherence is somewhat smaller than when not walking in phase coherence. We assume that this is due to the difference in the degrees of locomotive freedom: When being phase locked, you do not alter your cadence, so the only way to augment velocity is through increasing step length. When you don't walk in phase coherence with the musical beats, you have the freedom to increase both the walking cadence and the step length, which can result in larger effect sizes.

- **What type of musical features can affect walking or running kinematics and motivation?**
  The study in chapter 2 showed that specific musical features can impact walking velocity: Music with binary emphasis (accentuation in either pitch or volume on each alternating beat or once every four beats) is capable of increasing a walker's velocity, whereas music with ternary emphasis (accentuation once every three or six beats) is capable of decreasing the velocity. With binary accentuation patterns in music, the same beat/sound goes together with a specific foot. For example, the bass drum always coincides with one foot, whereas the snare coincides with the other foot. In other words, each footfall can be entrained by its own specific sound in the music. With ternary accentuation, a prominent beat switches constantly from coinciding with the right foot to coinciding with the left foot. We believe that the strength for increasing velocity with binary accentuation patterns lies in the fact that this type of music mirrors the walking movement pattern better.

  In addition, the study revealed a significant relationship between the motivational aspects of music and the velocity effect of music. This means that we can select music in advance that is both familiar and motivational for the participant in question, hence increasing the chances of music having an augmented effect on walking velocity.

  What remains unclear with respect to the relationship between motivation and velocity effect, is whether music increases walking velocity because the music arouses and therefore motivates, or because the velocity increase itself arouses and therefore motivates? In other words, is it perception or is it physical activity that leads to motivation, and is it mediated by arousal?

6.1.2 Music-to-movement alignment

Where the emphasis in the first part of this thesis was on the musical qualities, the emphasis in the second part was on the music alignment technology and its capacities to influence our running kinematics. Our main research question was:

Can we use music-manipulating techniques to spontaneously influence walking/running kinematics and motivation?

This question can also be answered positively. By changing the music tempo or the timing of the beats slightly in comparison to the initially tempo-matched and/or phase-coherent music, the running cadence and velocity could be influenced. As far as influencing motivation goes, continuous music-to-movement alignment techniques were enjoyed more than running with allochronic music. It seems logical that if an alignment strategy is more precise (follows the human movement better), that there is less entrainment or effort needed from the participant to adjust to the music. In addition, runners enjoyed being slowed-down less than being sped-up. This finding is in line with a study by Hobara, Sato, Sakaguchi, and Nakazawa (2012) that revealed that a 30% decrease in cadence results in higher joint loading rates, which can increase the risk for running related injuries. In addition, a study by Luedke, Heiderscheit, Williams, and Rauh (2016) showed that for high school runners a lower running cadence was associated with a greater likelihood of shin injury. Such an increased risk for running related injuries at lower step rates could explain our results where being slowed down decreased running comfort or enjoyment.

Secondary research questions concerning music-to-movement alignment techniques are discussed below:

- **What type of music-to-movement alignment technique results in highest level of entrainment?**
  Even if the tempo of the music is matched to the running cadence, music-to-movement alignment strategies that start the music in phase (beat on the step) result in a higher level of entrainment than strategies that do not start the music in phase. The difference lies in the fact that in the former case a runner does no longer have to make an effort to entrain with the beats, since the alignment strategy takes care of this. However, the highest level of entrainment is achieved with a music-to-movement alignment strategy that not only adjusts the timing of musical beats in the beginning, but also continuously. In most cases this results in continuous phase-locking (see chapter 3).

- **What type of music-to-movement alignment technique results in highest level of motivation?**

The study in chapter 3 showed that a music-to-movement alignment technique that results in the highest level of entrainment was rated more motivating than when the music was not aligned at all with the running cadence. If the music starts in phase (beat on the step) and is aligned continuously with the footfalls, the entrainment level is the highest and this is enjoyed the most. Such a continuous alignment strategy was also used in chapter 5 to manipulate running cadence. It became apparent that speeding a runner up is as motivating as running at a self-paced cadence, whereas being slowed down was enjoyed less.

- **Which music-manipulation techniques are most effective for influencing running cadence and/or velocity?**
  The studies in chapters 4 and 5 deal with manipulative alignment techniques. Chapter 4 explores if and how much music tempo can affect running tempo. Small music tempo deviations from the running tempo turned out effective in being able to change the running tempo. Deviations up to $+2.5\%$ or -2.5% had a respective increasing or decreasing tempo effect on running. Similar results came out of the study in chapter 5, where we tried to manipulate runners' cadence through shifting the musical beat slightly before or after the predicted moment of the footfall. The tested conditions where the manipulations were the smallest had the largest effect size. Both studies showed that the larger the timing differences between music and movement, the lower the level of entrainment and phase-locking with the music, thus reducing the attractor dynamics between the music and human movement.

- **Are there gender differences in running with music-manipulated technology?**
  Both the study with tempo manipulation techniques (chapter 4) and the one with relative phase angle manipulation techniques (chapter 5) presented gender differences. Although these studies did not reveal main gender effects, both showed gender interaction effects that came down to the fact that the effects on cadence were more pronounced for women than for men. Most likely this is related to women being more sensitive to the rhythmical characteristics in music (see Karageorghis et al., 1999).

6.2 Contributions to the research field

The work in this thesis contributed substantially to the research on entrainment. The concept of entrainment was at the basis of all of this thesis' studies, and it was the reason we always asked people to walk or run at their own comfortable speed or tempo. Previous research (Nombela et al., 2013; Roerdink et al., 2011) and in addition the results of our studies, indicate that the closer the musical tempo is to an individual's cadence, the higher the chance of entrainment and synchronization with the musical stimulus. This in turn leads to a stronger force of attraction that can be used to spontaneously manipulate runner's cadence.

Our studies showed the possibility for music to spontaneously influence walking or running movements. We think this is of added value to the general research on human-music interaction, but more precisely to gait rehabilitation research where people are usually instructed to synchronize their movements with a rhythmic stimulus like a metronome or music. Asking people to synchronize with such stimuli, actually is imposing a dual task on the subject. Although this still might have beneficial effects on walking, asking someone to synchronize comes down to increased demands, which reduces the therapeutic value of music-motor programmes (Rochester et al., 2005). Not instructing people to synchronize their movements with the musical beats is a more ecological approach, where the attractor dynamics of the musical tempo on walking cadence come into play naturally. However, not instructing could still lead to a self-imposed synchronization task. More research is needed to uncover the specific demands on gait when walking or running with music-to-movement alignment technology without instructions to synchronize. Special attention should be paid to how people having difficulty with dual (cognitive or motor) tasks are affected.

A third contribution of this thesis' work lies at the basis of making music-to-movement alignment technologies work, namely how to compile an appropriate music database. With 'appropriate' we refer to three aspects: music that (i) has suitable characteristics, like e.g. having a stable tempo and a clear beat, (ii) fits the task in tempo, meaning music from a suitable tempo range covering all possible movement tempi belonging to a task, and (iii) is liked or preferred by the user, to optimize the motivational aspect of the music for the user. Taking these three factors in account a semi-automatic music selection protocol was designed (see appendix A).

6.3 Future work

6.3.1 Entrainment, reward and motivation

Although this thesis revealed that running in synchrony with the musical beat was rated more motivating or was enjoyed more, than running with less synchrony or when being slowed down, the link with motivation could still be explored more thoroughly. For example, it is not yet clear what aspect of entrainment contributes the most to keeping motivation high. Is moving in synchrony with the music rewarding enough? Or is it the process of being entrained that is most rewarding? In other words, is it the transition of going from a non-synchronous state to a synchronous state that is rewarding? And if so, can we determine an optimal frequency of such transitions?

Related to this is the following question: Does a 0º relative phase angle correspond exactly to the perceived moment of stepping on the musical beat? Our experiments have shown the importance of chosing a musical stimulus that matches a person's cadence in tempo as closely as possible. And when we use a music-to-movement alignment technology that shifts the beats in order to influence running candence (chapter 5), the largest effect was achieved with very small phase angle manipulations. A requirement for being able to use small negative or positive shifts in phase angles is knowing very precisely which relative phase angle results in no increase or decrease of running cadence at all. More research should be done to define this optimal zero-influence point, and to explore if such a zero-influence point can be identified in general or if it depends on the person.

6.3.2 Gender specificity and individualization

Given our findings on gender (chapters 3 to 5), it would be good to invest more in optimizing human-music interactive systems for men and women or even on an individual basis. If men, or other individuals can only be influenced minimally through entrainment processes with the rhythmic part of the music, can they be influenced (more) by other musical parameters? Examples of such parameters could be pitch and loudness trajectories in the music, but also how familiar a song is to a user.

6.3.3 Optimization of the music selection protocol

Being able to select familiar or preferred music for each individual user would certainly have added value. The need to further automate the music selection process is therefore high. The protocol that has been developed so far, pays attention to selecting songs with a stable tempo (see appendix A). This is done by taking into account the variability (standard deviation) of the IBI durations. Unfortunately, a stable tempo does not automatically imply correct beat annotations. The durations between the beats might be very similar, but if the detected beats coincide with the off-beats, rather than the actual beats, this poses a problem for our music-to-movement alignment strategies. At the moment, this type of error is only detected through manual inspection of the beat annotations, which increases the duration of the selection process considerably. Possibly, such an inspection could be automated by verifying if the beat annotations correspond more with energy peaks in the low frequency subband(s) (bass or bass drum related sounds that typically indicate the beats) than with energy peaks in the high frequency subband(s) (e.g. high-hat sounds that are typically placed on the off-beat positions). The outcome of such a verification could be a calculated probability of the annotated beats being in the correct positions.

A second problem that extends the music selection process, are songs with partly correct beat annotations, and partly shifted, incorrect annotations on the off-beat positions. On the whole, the variability in IBI durations is low (indicating a stable tempo), since the small shifts where the correct annotations turn into incorrect annotations have only very limited effect on augmenting the IBI variability. Therefore these songs were considered in the next stage of the semi-automatic selection process: the manual inspection. It was only at this stage in the process that this type of annotation error was spotted. At the same time, it was labour-intensive to fix manually, because it usually concerned a substantial set of beats to be shifted. A potential way of automating the detection of such errors and excluding them from the following stages of the selection process, would be to calculate for each IBI the ratio between $IBI_t - IBI_{avg}$ and the average IBI duration (IBI_{avg}) in the song. If this ratio at certain time points exceeds a to be defined threshold (probably close to 0.5), this could be a good indicator of the above described beat annotation problem.

6.3.4 Expanded scope for music-based dynamic systems

Through all of our studies we have been using and further developing the DJogger system (Moens et al., 2014), a practical application to study and optimize a dynamical system, namely the bi-directional interaction between music technology and human movement. In the future we would like to extend this type of dynamical systems research in three possible directions:

- **Bring space into the equation,** through the use of a 3D sound installation. In the human-music interaction studies so far, we have mainly been interested in the dynamics of music and movement timing: how do the moments of the footsteps relate to the moments of the beats and vice versa? But music is more than simply timing of beats. It consists of (multi-layered) expressive patterns in pitch, loudness and timbre. In addition, a sound originates from a source and has a certain direction before being perceived by a human. Interesting new questions are, if and how our movement interaction with music changes if the music or sound is played from different sources/locations? And, if the spatialization of the music plays a role in this interaction, how can we employ this in practice (e.g. training with 3D sound headphones, a global 3D sound system that guids you through a museum, etc.)?

- **Multiple level human-music interaction.** Our results have shown the capability of music and music technology to influence running behaviour. The focus has been on the most salient moments in music, the beats, as influencers for the most salient moments in running gait, namely the footfalls. Music however, can be described as an accumulation of several layers, each with its own rhythm, tempo, melody, etc. In future studies, we could take the multi-layeredness of music as a basis for influencing two (or more) human physical or physiological patterns. An example is employing auditory biofeedback with music to sonify cadence through the main tempo of the music, and the breathing rhythm through another sonic layer in the music. With respect to locomotor-respiratory coupling (LRC) caution should however be taken, since possible energetic advantages due to a stronger frequency coupling are controversial. In fact, a study by O'Halloran, Hamill, McDermott, Remelius, and Van Emmerik (2012) concluded that it is the increased variability of frequency coupling when walking at a preferred stride frequency that results in lower oxygen consumption. Regarding implications for movement economy, these findings underline the importance of allowing for a sufficient degree of freedom in finding an optimal time-dependent frequency coupling. Music-based biofeedback should be designed to deal with this.

- **Study dynamic social interactions.** In this thesis our focus was on the interaction of a single human with music technology. Social interaction is the (conscious or spontaneous) cooperation between two or more humans. Like human-music interaction this can be seen as a dynamic system, where the interaction covers a scale from no interaction at all to an optimal state of (multi-level) interaction called homeostasis (see Leman, 2016).

  Moving in synchrony with a musical stimulus turned out to be an optimal state for attracting and hence influencing movement behaviour. We are interested to explore whether optimal states in social interaction can also be characterized through some form of entrainment or synchrony. To investigate this, we believe that music can be used as a tool to facilitate the research of social interaction. We could for instance instruct participants to play drums together, or to make vocal sounds together (e.g. like the Inuit's alternating throat singing). Relevant questions in this type of research would be: Can people that interact with each other through sounds or music, identify their optimal states of interaction? Can other people identify these states of homeostasis? Are there movement patterns or other quantitative measurements that can be linked to such moments of homeostasis? All these questions are relevant for finding out how we can help bring about more positive moments (homeostasis) in situations where social interaction is required.

6.4 Conclusions

Music has rhythm(s) and tempo, which is perfect for making use of the concept of entrainment. The attractor dynamics between two rhythms or tempi that are close together lead to being able to apply technology that adjusts the musical tempi or placements of the beats in order to spontaneously manipulate running tempo. This thesis shows that small music tempo deviations from the original self-paced running tempo can succesfully be used to influence running cadence, without the runner being instructed to take notice of the music, let alone being asked to synchronize with it. Similarly, a technique that introduces small (subconscious) shifts in timing of the beat with respect to the expected timing of the beat, was succesful at manipulating running cadence.

Although entrainment and phase locking were succesfully applied for influencing running cadence, the effect size was not equal for everyone. In fact, in the three studies where gender was introduced as a between-subjects factor, a gender-interaction effect on cadence was found, which unveiled a more pronounced effect of rhythmic entrainment for women than for men.

In addition to the driving force of the musical tempo, music also consists of intrinsic expressive features that have an impact on velocity of gait. Binary accentuation patterns (a presence or absence in every two or four beat periods) of such expressive features like pitch and loudness, proved to have an increasing effect on walking velocity, while ternary accentuation patterns (a presence or absence in every three or six beat periods) resulted in a decreased walking velocity.

Regarding the motivational aspect of using music to influence gait, we can conclude that (i) music was more motivating than a metronome stimulus, (ii) a high level of entrainment (continuous phase locking) was enjoyed more than a non-tempo-matching musical stimulus, (iii) being slowed down was enjoyed less than running with a beat-matching musical stimulus, and (iv) music with intrinsic velocity-increasing characteristics was rated more motivating.

Finally, these results were all obtained on self-paced walking or running cadence, so we can combine the benefits of training at your own tempo and/or intensity with the positive effects that could be achieved with human-music interaction systems as studied in this thesis. All of the above findings make a strong case for employing these or even more refined music-based biofeedback systems in sports (e.g. to reduce the risk of injury) or in gait rehabilitation programs.

My main contribution is: testing and developing a music selection protocol. This appendix is not a paper, but a description of the protocol.

A

Music Selection: a User- and Task-Specific Protocol

Abstract

Moving in synchrony with music has been shown to be motivating and less tiring. However, someone's favorite music might not be suitable for a task. Our goal was to define a set of tools to analyze and select songs that are suitable for running or walking, taking into account personal music preferences. In preparation of studies on using tempo-matched music for walking or running, music databases had to be created. Participants in the studies were asked to give a list of their favorite music. Starting from these user preferences and similar songs, all songs were analyzed for their usability in the tasks of walking and running. The analysis involved i) automatic beat tracking, ii) filtering for task specific tempo (80-130 beats per minute for walking and 130-200 for running), iii) automatic stability check of the musical tempo, and iv) a final auditory check of the beats for the songs still available after previous steps. For a study on gait rehabilitation for French PD patients the defined protocol was used to create a database with +/-250 songs, covering six different genres (e.g. disco and variété). In addition, a music database of similar size was created for a study on running. The amount of songs that needed to be checked manually was reduced, thus saving time.

A.1 Introduction

At the heart of creating a personalized music database to be used during walking or running, are two aspects: the running or walking cadence of the user (to define the tempo of the music) and the user's personal musical preference. Since the choice of music is limited to music with a tempo matching the user's cadence, and other musical qualities necessary to increase the benefits of moving to music, it is impossible for the user to simply use his or her own playlist. However, it is possible to start from prototypical users' preferences to create a music database containing a sufficient number of songs from different genres with adequate musical qualities from which a user can select an individualized playlist. In Figure A.1 the workflow for this process is shown.

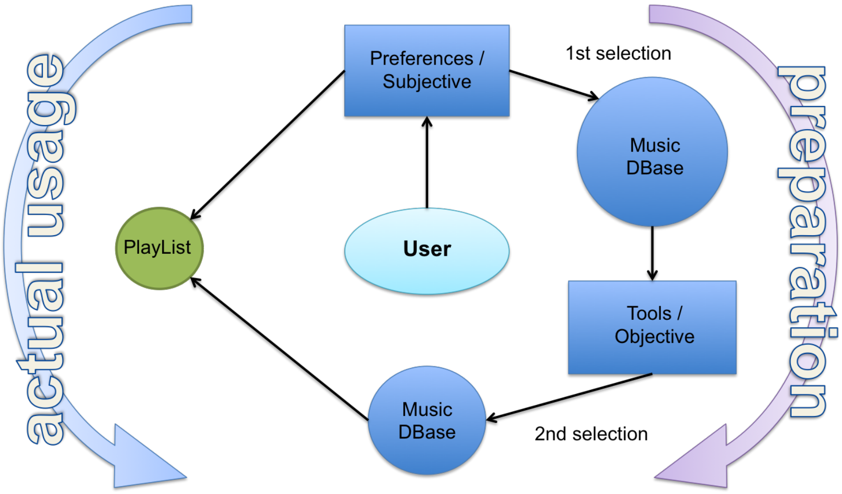
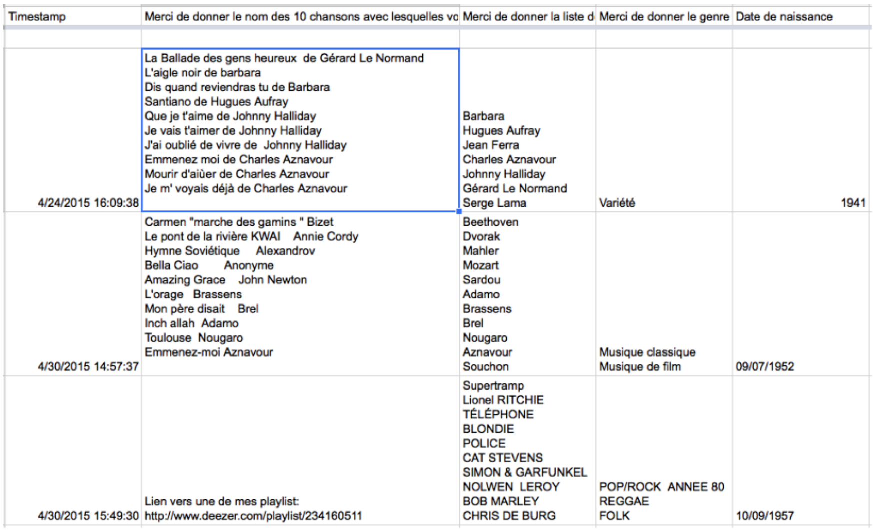


Figure A.1: Workflow for music database creation.

For (almost) all of the music-to-movement alignment strategies that were tested in this thesis beat annotated music is required. In order to match the music with the human movement, the music manipulation technology needs to know exactly where the beats are located in time. Everything starts with the user when we design a music database with beat annotated music. The 'user', meaning an actual person that will take part in an experiment or a group of prototypical users: with similar demographic background. Figure A.2 shows part of a questionnaire that was used as a basis to create a music database for a group of French participants with Parkinson's Disease. These music suggestions are combined with equivalent music tracks or more songs from the same period in time, to form the first selection. A number of tools and a manual check are subsequently used to filter this selection down to a subset of useable music tracks.



Timestamp	Merci de donner le nom des 10 chansons avec lesquelles vo	Merci de donner la liste d	Merci de donner le genre	Date de naissance
4/24/2015 16:09:38	La Ballade des gens heureux de Gérard Le Normand L'aigle noir de barbara Dis quand reviendras tu de Barbara Santiano de Hugues Aufray Que je t'aime de Johnny Halliday Je vais t'aimer de Johnny Halliday J'ai oublié de vivre de Johnny Halliday Emmenez moi de Charles Aznavour Mourir d'aiùer de Charles Aznavour Je m' voyais déjà de Charles Aznavour	Barbara Hugues Aufray Jean Ferra Charles Aznavour Johnny Halliday Gérard Le Normand Serge Lama	Variété	1941
4/30/2015 14:57:37	Carmen "marche des gamins " Bizet Le pont de la rivière KWAI Annie Cordy Hymne Soviétique Alexandrov Bella Ciao Anonyme Amazing Grace John Newton L'orage Brassens Mon père disait Brel Inch allah Adamo Toulouse Nougaro Emmenez-moi Aznavour	Beethoven Dvorak Mahler Mozart Sardou Adamo Brassens Brel Nougaro Aznavour Souchon	Musique classique Musique de film	09/07/1952
4/30/2015 15:49:30	Lien vers une de mes playlist: http://www.deezer.com/playlist/234160511	Supertramp Lionel RITCHIE TÉLÉPHONE BLONDIE POLICE CAT STEVENS SIMON & GARFUNKEL NOLWEN LEROY BOB MARLEY CHRIS DE BURG	POP/ROCK ANNEE 80 REGGAE FOLK	10/09/1957

Figure A.2: Questionnaire example: music preferences of three French PD patients.

In addition to the user preferences we also need to take into account the typical cadence range for walking and running. In case of the PD patients, results from walking tests collected from PD patients at CHRU, the university hospital in Montpellier, revealed a cadence range of 89 to 124 SPM. A music database for PD patients would therefore need to cover songs from 80 to 130 BPM. For running the typical cadence ranges from 130 to 200 SPM, requiring a music database with songs from 130 to 200 BPM.

A.2 Database size calculation

The music-to-movement alignment strategies used in this thesis are capable of modifying the tempo of a song without changing the pitch (e.g. with élastique efficient from ZPlane). In order to maintain the characteristics of a song the maximum tempo adaptation is set to 5%. A tempo change within 4% is even considered to be unnoticeable to the listener (Levitin, 2006).

Below two example database size calculations are given. With respect to a music database for French PD patients, the following factors were taken into account to calculate the minimum size:

- Average SPM for walking lies around 100 SPM
- For a cadence of 100 SPM, music tracks can be selected (and adapted) from 95 BPM (-5%) to 105 BPM (+5%): a range of 10 BPM

- Total BPM range of the database is from 80 to 130 BPM: 5 bins of 10 BPM
- PD patients are requested to walk 30 min per training session: duration of approximately 10 songs
- A PD patient should be able to choose music from 5 different genres in order to provide sufficient music material per individual
- Result: 5 BPM bins x 10 songs x 5 genres = 250 songs

The second example is a music database that was created for healthy recreational runners. The minimum database size calculation is more or less the same:

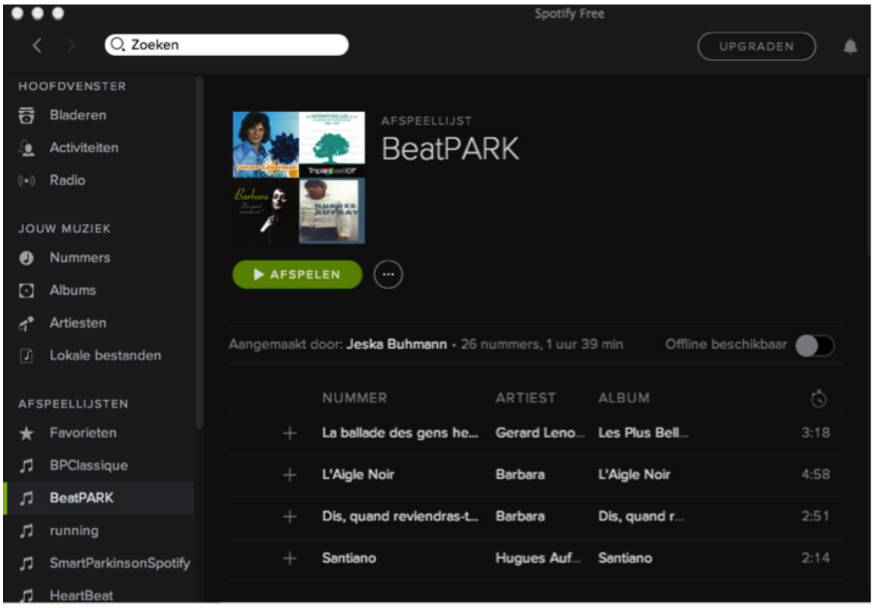
- Average SPM for running lies around 160 SPM
- For a cadence of 160 SPM, music tracks can be selected (and adapted) from 152 BPM (-5%) to 168 BPM (+5%): a range of 16 BPM
- Total BPM range of the databaseis from 120 to 200 BPM: 5 bins of 16 BPM
- Runners are requested to run 30 min per training session: duration of approximately 10 songs
- A runner should be able to choose music from 5 different genres in order to provide sufficient music material per individual
- Result: 5 BPM bins x 10 songs x 5 genres = 250 songs

In both cases the minimum number of music tracks to be selected is 250. If a user would have a very stable tempo (music selection from only one BPM bin) and would only like one genre of music, this database size would cover different music tracks for at least one training session.

A.3 Different steps in the selection process

A.3.1 User- and task-specific music selection and filtering

Based on individual music preferences an initial music database was created. This was done with the help of Spotify (see Figure A.3). Not only could we add preferences to a playlist, we also used other functionalities to add similar tracks to the list. For example, the radio function automatically generates a list of music tracks that have similar musical features or tracks from other artists within the same genre. In addition, the search function made it possible to search more directly for music from specific artists, genres, periods in time, or even music with an explicit tempo.



Aangemaakt door: **Jeska Buhmann** • 26 nummers, 1 uur 39 min

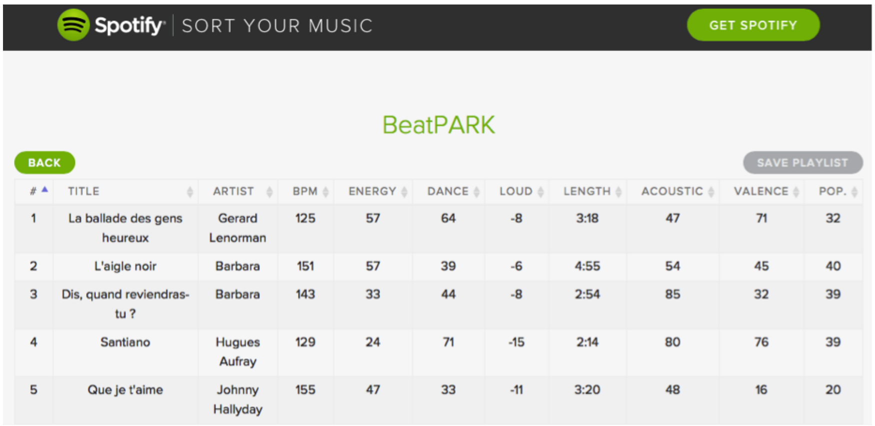
NUMMER	ARTIEST	ALBUM	⏱
La ballade des gens he...	Gerard Leno...	Les Plus Bell...	3:18
L'Aigle Noir	Barbara	L'Aigle Noir	4:58
Dis, quand reviendras-t...	Barbara	Dis, quand r...	2:51
Santiano	Hugues Auf...	Santiano	2:14

Figure A.3: Initial music selection stage through creating a Spotify playlist.

In this first step of the music selection process we already try to take the tempo requirements for the task into account as much as possible. On the one hand, this is done simply by listening (partially) to music tracks and discarding them from further processing if (i) the tempo of the track is too unstable, (ii) there are tempo changes within the track, or (iii) the meter or the rhythm of the track is assessed too difficult. On the other hand, an online tool "Sort Your Music" from Echonest is helpful in preselecting music tracks. It can be used to give a number of musical parameters for all the tracks in a Spotify playlist of your choice (see Figure A.4). Most importantly, it generates an average BPM value per music track, which is used to decide whether the track can be kept for further processing or not. Another interesting feature is the Dance parameter, a measure of how easy the song is to dance to (from 0 to 100). Since a high danceability often goes hand in hand with the presence of clear and stable beats, we also use this parameter to decide whether or not to further process a music track (yes, if the value was bigger than 50).

A.3.2 Automatic beat tracking and tempo stability check

In order to investigate the tempo stability of the music tracks with more precision and to be able to extract beats with a beat tracker, we need the actual audio in Wav format. We therefore acquire the remaining songs from the initial selection via iTunes or we access the songs through other available music databases. If



BeatPARK

#	TITLE	ARTIST	BPM	ENERGY	DANCE	LOUD	LENGTH	ACOUSTIC	VALENCE	POP.
1	La ballade des gens heureux	Gerard Lenorman	125	57	64	-8	3:18	47	71	32
2	L'aigle noir	Barbara	151	57	39	-6	4:55	54	45	40
3	Dis, quand reviendras-tu ?	Barbara	143	33	44	-8	2:54	85	32	39
4	Santiano	Hugues Aufray	129	24	71	-15	2:14	80	76	39
5	Que je t'aime	Johnny Hallyday	155	47	33	-11	3:20	48	16	20

Figure A.4: Online tool "Sort Your Music" for additional song information of Spotify playlist.

needed the audio format is coverted to wav format with a tool like Adobe Audition. For tracks acquired through iTunes it was necessary to convert from m4a to wav format. We also use Adobe Audition to edit the songs if necessary, e.g. cutting of intros or outros that have other musical qualities than the rest of the song.

The automatic beat tracking of the music tracks is carried out by the Essentia beat tracker (Bogdanov et al., 2013). This tool takes a .wav file with 44100 Hz sampling rate as input and generates a .json file as output. The estimated beat locations can be extracted from a .json file with a Matlab script.

After the beat positions have been extracted, we use another Matlab script to calculate a number of BPM statistics to find out more about the stability of the beats. The following parameters are written to an output file:

- Title of the song
- BPM of the song, extracted with the Essentia beat tracker
- Average smoothed BPM
- BPM range: difference between highest and lowest BPM in the song
- Standard deviation of the BPM

There are different indicators for unstable beats throughout the song: a big difference between the Essentia and the smoothed BPM, a big difference between the highest and lowest BPM in the song, and a big standard deviation of the BPM. All of these indicaters are used to discard music tracks from the final music database. With respect to the BPM range, the threshold for most of our music selection was set at 5 BPM: if the difference between the highest and the lowest BPM is larger than 5 BPM, the music track would be discarded. And with respect to the standard deviation of the BPM, experience thought us that values over 2 BPM usually indicate severe problems in the beat annotations (too much work to automatically or manually correct).

In addition to the BPM statistics, the Matlab script generates BPM plots, to enable us to explore the BPM progress in time visually. Figure A.5 is an example of such a graph. Visual inspection can have added value if the BPM statistics are not specific enough to decide on further processing.

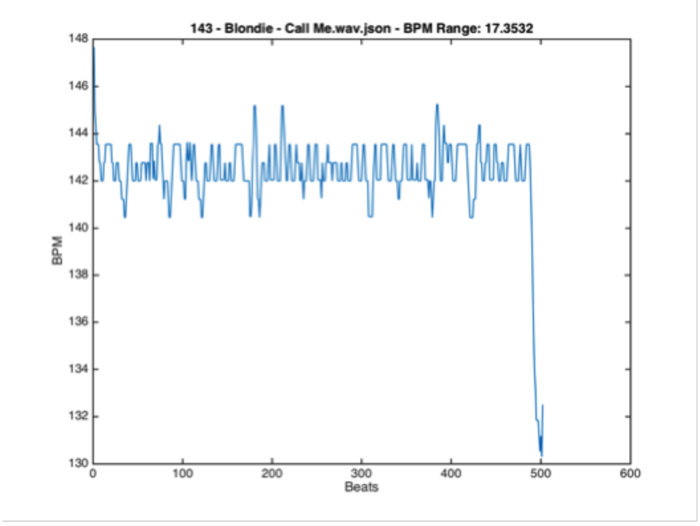


Figure A.5: BPM graph: an example of a stable BPM throughout the song.

A.3.3 Manual validation and correction step

The fact is that a stable BPM does not necessarily mean correct beat annotations. It might be the case that the beat tracker assigns beats to the ’off’-beat positions, or places them sligtly before or after the beat offset. Therefore, the music tracks that made it so far through the selection process are manually checked. This is done with BeatRoot (Dixon, 2007), an automatic beat tracker with a graphical user interface (see A.6). An existing beat annotation file can be imported or the tool can be used to generate new beat annotations. BeatRoot enables listening to a music track while sonifying the annotated beats with metronome ticks. Errors can either be spotted auditory or visually through locating mismatches between the musical beat (usually in the lower frequency band) and the metronome tick. If the number of misaligned beats is not too large, these errors can easily be corrected in the same tool by clicking a misaligned beat (a black vertical line), holding the button down and shifting the beat to the correct position. The final result can then be saved to a file with all the beat annotation times.

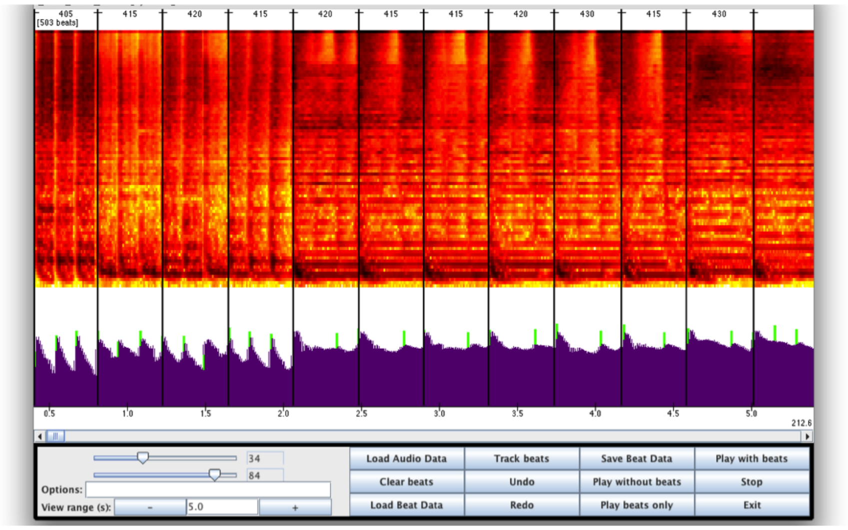


Figure A.6: BeatRoot's graphical user interface

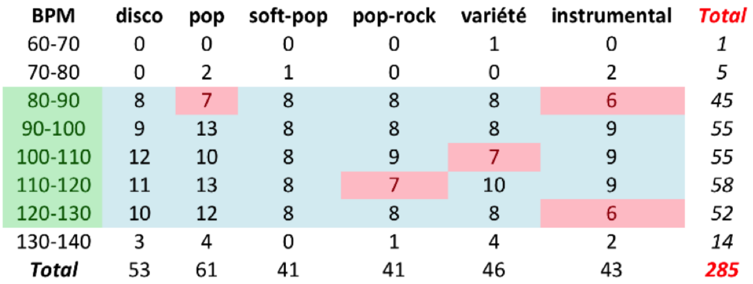
A.4 Results

For the two databases where we calculated a minimum size of 250 music tracks, we finally selected a bit more: 285 music tracks for the French PD database and 354 for the healthy recreational runners. Figure A.7 and A.8 give an overview of the number of music tracks per BPM bin and per genre.

To cover most of the user preferences from the French PD patients it was decided to have six instead of five genres. Therefore, our goal was to have at least eight instead of ten songs per 10 BPM-range. In the cases where we did not find eight or more suitable music tracks, we added extra tracks to adjacent BPM bins. Furthermore, to ensure there are enough different songs to be played during one training session, participants were asked to select at least two of the six genres, before starting a walking session.

A.5 Conclusion and future work

We designed a semi-automatic procedure for creating task- and user-specific playlists that can be used together with music-to-movement alignment technology in sport



BPM	disco	pop	soft-pop	pop-rock	variété	instrumental	*Total*
60-70	0	0	0	0	1	0	*1*
70-80	0	2	1	0	0	2	*5*
80-90	8	7	8	8	8	6	*45*
90-100	9	13	8	8	8	9	*55*
100-110	12	10	8	9	7	9	*55*
110-120	11	13	8	7	10	9	*58*
120-130	10	12	8	8	8	6	*52*
130-140	3	4	0	1	4	2	*14*
Total	53	61	41	41	46	43	***285***

Figure A.7: Distribution of songs for French PD music database: number of songs per genre and BPM range

BPM	pop	rock	electro	swing	world	*Total*
-130	2	0	8	1	1	*12*
130-144	14	15	11	15	14	*69*
144-158	12	27	12	11	13	*75*
158-172	16	25	14	13	15	*83*
172-186	13	25	10	14	11	*73*
186-200	9	9	5	7	5	*35*
200+	1	2	1	1	2	*7*
Total	67	103	61	62	61	***354***

Figure A.8: Distribution of songs for healthy runners music database: number of songs per genre and BPM range

activities such as running or cycling or in gait rehabilitation programs. This protocol resulted in reduced (manual) listening time, because the automatic beat annotation and validation steps were able to discard music tracks, that otherwise probably would have been discarded during the final corrective listening phase of the process. As an example, in the creation process of a music database for French PD patients we started out with 605 and ended up with 285 music tracks (47%). Only 15% of the songs that made it to the final validation and correction step were not suitable for further use.

Future improvements on the current protocol should aim at further reducing the proportion of music tracks that make it to the final phase of the process, yet still require too much manual corrective work to invest in. Ideas for such improvements involve better beat annotation tools or more specialised beat validation tools such as described in section 6.3.3.

My main contribution is: co-writing the paper, with emphasis on the following sections: “Music and Motion”, “Trancing”, “Relevance for Sonification Purposes”, “Auditory-Motor Synchronization”, and “The Role of Expression”.

B

3Mo: a Model for Music-Based Biofeedback

Maes, P.-J., J. Buhmann, and M. Leman

In *Frontiers in Neuroscience*, 2016, *10*(548)

Abstract

In the domain of sports and motor rehabilitation, it is of major importance to regulate and control physiological processes and physical motion in most optimal ways. For that purpose, real-time auditory feedback of physiological and physical information based on sound signals, often termed “sonification,” has been proven particularly useful. However, the use of music in biofeedback systems has been much less explored. In the current article, we assert that the use of music, and musical principles, can have a major added value, on top of mere sound signals, to the benefit of psychological and physical optimization of sports and motor rehabilitation tasks. In this article, we present the 3Mo model to describe three main functions of music that contribute to these benefits. These functions relate the power of music to Motivate, and to Monitor and Modify physiological and physi-

cal processes. The model brings together concepts and theories related to human sensorimotor interaction with music, and specifies the underlying psychological and physiological principles. This 3Mo model is intended to provide a conceptual framework that guides future research on musical biofeedback systems in the domain of sports and motor rehabilitation.

My main contribution is: co-writing the chapter with emphasis on the parapraphs on “Entrainment” and “Dancing and walking”.

C

The Empowering Effects of Being Locked into the Beat of the Music

Leman, M., J. Buhmann, and E. Van Dyck

In C. Wöllner (Eds.), *Body, Sound and Space in Music and Beyond: Multimodal Explorations*, 2017, 13–28. London, UK: Routledge.

Abstract

A regular rhythm in music is a strong driver for establishing a synchronised human rhythm. Typically, a human rhythm tends to go along with the musical rhythm in such a way that a salient feature of the human rhythm matches the timing of a salient feature of the musical rhythm. For example, when we tap our finger on a desk, we can match it with the timing of a metronome tick and, when we walk, we can match the cadence of our footfall with the timing of the beat of the music. Salient moments of the rhythm (tap, footfall, beat) are markers for synchronisation. The performer uses them to establish a synchronised action, while the scientist employs them in order to study this particular type of action. But what are the underlying mechanisms behind music-to-movement synchronisation? And which effects does it generate? The goal of this chapter is to introduce and offer

different views on the study of these underlying mechanisms, and to show how being locked to the beat of the music can pave the way for an overall empowerment effect, that is, the feeling that music affords energy and contributes to an increase in autonomy and self-determination. In this chapter, we present some recent theoretical and empirical work that focuses on movement rhythm such as walking, running, cycling and dancing. First, we introduce a theoretical umbrella perspective on synchronisation and embodied interaction with music. Then, we focus on some concrete studies that tell us something about the mechanisms of resonance, entrainment and emulation. Finally, we shed some light on possible empowering effects of music.

References

Ajzen, I. and M. Fishbein (1977). Attitude-behavior relations: A theoretical analysis and review of empirical research. *Psychological Bulletin 84*(5), 888–918.

Alter, D. A., M. O'Sullivan, P. I. Oh, D. A. Redelmeier, S. Marzolini, R. Liu, M. Forhan, M. Silver, J. M. Goodman, and L. R. Bartel (2015). Synchronized personalized music audio-playlists to improve adherence to physical activity among patients participating in a structured exercise program: a proof-of-principle feasibility study. *Sports medicine-open 1*(23), 1–13.

Atkinson, G., D. Wilson, and M. Eubank (2004). Effects of music on work-rate distribution during a cycling time trial. *International Journal of Sports Medicine 25*(08), 611–615.

Berens, P. (2009, September). CircStat: a MATLAB toolbox for circular statistics. *Journal of Statistical Software 31*(10), 1–21.

Bertram, J. E. and A. Ruina (2001). Multiple walking speed-frequency relations are predicted by constrained optimization. *Journal of Theoretical Biology 209*(4), 445–453.

Bogdanov, D., N. Wack, E. Gómez, S. Gulati, P. Herrera, O. Mayor, G. Roma, J. Salamon, J. R. Zapata, X. Serra, et al. (2013). Essentia: An audio analysis library for music information retrieval. In *ISMIR*, pp. 493–498.

Bood, R. J., M. Nijssen, J. van der Kamp, and M. Roerdink (2013). The power of auditory-motor synchronization in sports: enhancing running performance by coupling cadence with the right beats. *PLOS ONE 8*(8), doi:10.1371/journal.pone.0070758.

Borg, G. (1998). *Borg's perceived exertion and pain scales.* Champaign, IL: Human kinetics.

Brownley, K. A., R. G. McMurray, and A. C. Hackney (1995). Effects of music on physiological and affective responses to graded treadmill exercise in trained and untrained runners. *International Journal of Psychophysiology 19*(3), 193–201.

Buhmann, J., F. Desmet, B. Moens, E. Van Dyck, and M. Leman (2016). Spontaneous velocity effect of musical expression on self-paced walking. *PLOS ONE 11*(5), doi:10.1371/journal.pone.0154414.

Cohen, S. L., C. Paradis, and L. M. LeMura (2007). The effects of contingent-monetary reinforcement and music on exercise in college students. *Journal of Sport Behavior 30*(2), 146–160.

Cole, Z. and H. Maeda (2015). Effects of listening to preferential music on sex differences in endurance running performance. *Perceptual and Motor Skills 121*(2), 390–398.

Danion, F., E. Varraine, M. Bonnard, and J. Pailhous (2003). Stride variability in human gait: the effect of stride frequency and stride length. *Gait & Posture 18*(1), 69–77.

de Bruin, N., J. B. Doan, G. Turnbull, O. Suchowerksy, S. Bonfield, B. Hu, and L. A. Brown (2010). Walking with music is a safe and viable tool for gait training in Parkinson's disease: the effect of a 13-week feasibility study on single and dual task walking. *Parkinson's Disease 2010*, doi:10.4061/2010/483530.

Dixon, S. (2007). Evaluation of the audio beat tracking system BeatRoot. *Journal of New Music Research 36*(1), 39–50.

Edworthy, J. and H. Waring (2006). The effects of music tempo and loudness level on treadmill exercise. *Ergonomics 49*(15), 1597–1610.

Eliakim, M., E. Bodner, Y. Meckel, D. Nemet, and A. Eliakim (2013). Effect of rhythm on the recovery from intense exercise. *The Journal of Strenght & Conditioning Research 27*(4), 1019–1024.

Elliott, D., S. Carr, and D. Orme (2005). The effect of motivational music on sub-maximal exercise. *European Journal of Sport Science 5*(2), 97–106.

Faul, F., E. Erdfelder, A.-G. Lang, and A. Buchner (2007). G* power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods 39*(2), 175–191.

Ferber, R., B. Noehren, J. Hamill, and I. Davis (2010). Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *Journal of Orthopaedic & Sports Physical Therapy 40*(2), 52–58.

Franěk, M., L. van Noorden, and L. Režný (2014, December). Tempo and walking speed with music in the urban context. *Frontiers in Psychology 5*(1361), doi:10.3389/fpsyg. 2014.01361.

Fritz, T. H., S. Hardikar, M. Demoucron, M. Niessen, M. Demey, O. Giot, Y. Li, J.-D. Haynes, A. Villringer, and M. Leman (2013). Musical agency reduces perceived exertion during strenuous physical performance. *Proceedings of the National Academy of Sciences 110*(44), 17784–17789.

Fritz, T. H., L. Schneider, and A. Villringer (2016). The band effect—physically strenuous music making increases esthetic appreciation of music. *Frontiers in Neuroscience 10*(448), 1–7.

Godøy, R. I. and M. Leman (2010). *Musical gestures: Sound, movement, and meaning*. New York: Routledge.

Grafarend, E. W. (2006). *Linear and Nonlinear Models: Fixed Effects, Random Effects, and Mixed Models*. Berlin; New York: Walter de Gruyter.

Heiderscheit, B. C., E. S. Chumanov, M. P. Michalski, C. M. Wille, and M. B. Ryan (2011, February). Effects of step rate manipulation on joint mechanics during running. *Medicine and Science in Sports and Exercise 43*(2), 296–302.

Hobara, H., T. Sato, M. Sakaguchi, and K. Nakazawa (2012). Step frequency and lower extremity loading during running. *International Journal of Sports Medicine 33*(4), 310–313.

Hoffmann, C. P., G. Torregrosa, and B. G. Bardy (2012). Sound stabilizes locomotor-respiratory coupling and reduces energy cost. *PLOS ONE 7*(9), doi:10.1371/journal.pone.0045206.

Honing, H., F. L. Bouwer, and G. P. Háden (2014). Perceiving temporal regularity in music: The role of auditory event-related potentials (erps) in probing beat perception. In H. Merchant and V. de Lafuente (Eds.), *Neurobiology of interval timing*, pp. 305–323. New York: Springer.

Hove, M. J., K. Suzuki, H. Uchitomi, S. Orimo, and Y. Miyake (2012). Interactive rhythmic auditory stimulation reinstates natural 1/f timing in gait of parkinson's patients. *PLOS ONE 7*(3), doi:10.1371/journal.pone.0032600.

Hsu, D. Y., L. Huang, L. F. Nordgren, D. D. Rucker, and A. D. Galinsky (2015, August). The music of power: Perceptual and behavioral consequences of powerful music. *Social Psychological and Personality Science 6*(1), 75–83.

Hutchinson, J. C. and G. Tenenbaum (2007). Attention focus during physical effort: The mediating role of task intensity. *Psychology of Sport and Exercise 8*(2), 233–245.

Janata, P., S. T. Tomic, and J. M. Haberman (2012). Sensorimotor coupling in music and the psychology of the groove. *Journal of Experimental Psychology: General 141*(1), 54–75.

Jarraya, M., H. Chtourou, A. Aloui, O. Hammouda, K. Chamari, A. Chaouachi, and N. Souissi (2012). The effects of music on high-intensity short-term exercise in well trained athletes. *Asian Journal of Sports Medicine 3*(4), 233–238.

Karageorghis, C. I. (2008). The scientific application of music in sport and exercise. In A. M. Lane (Ed.), *Sport and exercise psychology*, pp. 109–137. London: Hodder Education.

Karageorghis, C. I., L. Jones, and D. C. Low (2006). Relationship between exercise heart rate and music tempo preference. *Research Quarterly for Exercise and Sport 77*(2), 240–250.

Karageorghis, C. I., D. A. Mouzourides, D.-L. Priest, T. A. Sasso, D. J. Morrish, and C. L. Walley (2009). Psychophysical and ergogenic effects of synchronous music during treadmill walking. *Journal of Sport and Exercise Psychology 31*(1), 18–36.

Karageorghis, C. I. and D.-L. Priest (2012a). Music in the exercise domain: a review and synthesis (part i). *International Review of Sport and Exercise Psychology 5*(1), 44–66.

Karageorghis, C. I. and D.-L. Priest (2012b). Music in the exercise domain: a review and synthesis (part ii). *International Review of Sport and Exercise Psychology 5*(1), 67–84.

Karageorghis, C. I., D.-L. Priest, P. C. Terry, N. L. D. Chatzisarantis, and A. M. Lane (2006). Redesign and initial validation of an instrument to assess the motivational qualities of music in exercise: the Brunel Music Rating Inventory-2. *Journal of Sports Sciences 24*(8), 899–909.

Karageorghis, C. I., P. C. Terry, and A. M. Lane (1999). Development and initial validation of an instrument to assess the motivational qualities of music in exercise and sport: The brunel music rating inventory. *Journal of Sports Sciences 17*(9), 713–724.

Karageorghis, C. I., P. C. Terry, A. M. Lane, D. T. Bishop, and D.-l. Priest (2012). The bases expert statement on use of music in exercise. *Journal of Sports Sciences 30*(9), 953–956.

Kelso, J. S. (1995). *Dynamic patterns: The self-organization of brain and behavior.* Cambridge, MA: MIT press.

Kendzierski, D. and K. J. DeCarlo (1991). Physical activity enjoyment scale: Two validation studies. *Journal of Sport and Exercise Psychology 13*(1), 50–64.

Kenyon, G. P. and M. H. Thaut (2003). Rhythm-driven optimization of motor control. *Recent Research Developments in Biomechanics 1*, 29–47.

Kuo, A. D. (2001). A simple model of bipedal walking predicts the preferred speed-step length relationship. *Journal of Biomechanical Engineering-Transactions of the Asme 123*, 264–269.

Large, E. W. (2000). On synchronizing movements to music. *Human Movement Science 19*(4), 527–566.

Leman, M. (2007). *Embodied music cognition and mediation technology*. Cambridge, MA: MIT Press.

Leman, M. (2016). *The expressive moment: How interaction (with music) shapes human empowerment*. Cambridge, MA: MIT press.

Leman, M., D. Moelants, M. Varewyck, F. Styns, L. van Noorden, and J.-P. Martens (2013, July). Activating and relaxing music entrains the speed of beat synchronized walking. *PLOS ONE 8*(7), doi:10.1371/journal.pone.0067932.

Leow, L.-A., T. Parrott, and J. A. Grahn (2014). Individual differences in beat perception affect gait responses to low- and high-groove music. *Frontiers in Human Neuroscience 8:811*, doi:10.3389/fnhum.2014.00811.

Levitin, D. (2006). *This is your brain on music: the science of a human obsession*. New York: Dutton.

Lim, H. B., C. I. Karageorghis, L. M. Romer, and D. T. Bishop (2014). Psychophysiological effects of synchronous versus asynchronous music during cycling. *Medicine and Science in Sports and Exercise 46*(2), 407–413.

Lopresti-Goodman, S. M., M. J. Richardson, P. L. Silva, and R. Schmidt (2008). Period basin of entrainment for unintentional visual coordination. *Journal of Motor Behavior 40*(1), 3–10.

Luedke, L. E., B. C. Heiderscheit, D. Williams, and M. J. Rauh (2016). Influence of step rate on shin injury and anterior knee pain in high school runners. *Medicine and Science in Sports and Exercise 48*(7), 1244–1250.

MacDougall, H. G. and S. T. Moore (2005). Marching to the beat of the same drummer: the spontaneous tempo of human locomotion. *Jourrnal of Applied Physiology 99*, 1164–1173.

Madison, G. and G. Sioros (2014). What musicians do to induce the sensation of groove in simple and complex melodies, and how listeners perceive it. *Frontiers in Psychology 5*(894), doi:10.3389/fpsyg.2014.00894.

Maes, P.-J., J. Buhmann, and M. Leman (2016). 3mo: A model for music-based biofeedback. *Frontiers in Neuroscience 10*(548), doi:10.3389/fnins.2016.00548.

Maes, P.-J., M. Leman, C. Palmer, and M. M. Wanderley (2013). Action-based effects on music perception. *Frontiers in Psychology 4*(1008), doi:10.3389/fpsyg.2013.01008.

Mancini, M., L. King, A. Salarian, L. Holstrom, J. McNames, and F. Horak (2012). Mobility Lab to assess balance and gait with synchronized body-worn sensors. *Journal of Bioengineering and Biomedical Science 1*, 2–7.

Meister, I. G., T. Krings, H. Foltys, B. Boroojerdi, M. Müller, R. Töpper, and A. Thron (2004, May). Playing piano in the mind - an fMRI study on music imagery and performance in pianists. *Cognitive Brain Research 19*(3), 219–228.

Mendonça, C., M. Oliveira, L. Fontes, and J. Santos (2014). The effect of instruction to synchronize over step frequency while walking with auditory cues on a treadmill. *Human Movement Science 33*, 33–42.

Moens, B. and M. Leman (2015). Alignment strategies for the entrainment of music and movement rhythms. *Annals of the New York Academy of Sciences 1337*(1), 86–93.

Moens, B., C. Muller, L. van Noorden, M. Franěk, B. Celie, J. Boone, J. Bourgois, and M. Leman (2014, December). Encouraging spontaneous synchronisation with D-Jogger, an adaptive music player that aligns movement and music. *PLOS ONE 9*(12), doi:10.1371/ journal.pone.0114234.

Mohammadzadeh, H., B. Tartibiyan, and A. Ahmadi (2008). The effects of music on the perceived exertion rate and performance of trained and untrained individuals during progressive exercise. *Facta Universitatis-Series: Physical Education and Sport 6*(1), 67–74.

Mormann, F., K. Lehnertz, P. David, and C. E. Elger (2000). Mean phase coherence as a measure for phase synchronization and its application to the eeg of epilepsy patients. *Physica D: Nonlinear Phenomena 144*(3), 358–369.

Mullen, S. P., E. A. Olson, S. M. Phillips, A. N. Szabo, T. R. Wójcicki, E. L. Mailey, N. P. Gothe, J. T. Fanning, A. F. Kramer, and E. McAuley (2011). Measuring enjoyment of physical activity in older adults: invariance of the physical activity enjoyment scale (paces) across groups and time. *International Journal of Behavioral Nutrition and Physical Activity 8*(103), doi:10.1186/1479–5868–8–103.

Nakamura, P. M., G. Pereira, C. B. Papini, F. Y. Nakamura, and E. Kokubun (2010). Effects of preferred and nonpreferred music on continuous cycling exercise performance. *Perceptual and Motor Skills 110*(1), 257–264.

Nessler, J. A. and S. J. Gilliland (2010). Kinematic analysis of side-by-side stepping with intentional and unintentional synchronization. *Gait & Posture 31*(4), 527–529.

Nethery, V. (2002). Competition between internal and external sources of information during exercise: influence on rpe and the impact of the exercise load. *Journal of Sports Medicine and Physical Fitness 42*(2), 172–178.

Noehren, B., I. Davis, and J. Hamill (2007). Asb clinical biomechanics award winner 2006: Prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clinical Biomechanics 22*(9), 951–956.

Nombela, C., L. E. Hughes, A. M. Owen, and J. A. Grahn (2013). Into the groove: can rhythm influence parkinson's disease? *Neuroscience & Biobehavioral Reviews 37*, 2564–2570.

O'Halloran, J., J. Hamill, W. J. McDermott, J. G. Remelius, and R. E. Van Emmerik (2012). Locomotor-respiratory coupling patterns and oxygen consumption during walking above and below preferred stride frequency. *European Journal of Applied Physiology 112*(3), 929–940.

Pellett, T. L. (1994). Children's stereotypical perceptions of physical activities: Ak—12 analysis. *Perceptual and Motor Skills 79*(3), 1128–1130.

Priest, D.-L. and C. I. Karageorghis (2008). A qualitative investigation into the characteristics and effects of music accompanying exercise. *European Physical Education Review 14*(3), 347–366.

Priest, D.-L., C. I. Karageorghis, and N. C. C. Sharp (2004). The characteristics and effects of motivational music in exercise settings: the possible influence of gender, age, frequency of attendance, and time of attendance. *Journal of Sports Medicine and Physical Fitness 44*, 77–86.

Ramji, R., U. Aasa, J. Paulin, and G. Madison (2016). Musical information increases physical performance for synchronous but not asynchronous running. *Psychology of Music 44*(5), 984–995.

Razon, S., I. Basevitch, W. Land, B. Thompson, and G. Tenenbaum (2009). Perception of exertion and attention allocation as a function of visual and auditory conditions. *Psychology of Sport and Exercise 10*(6), 636–643.

Reenalda, J., M. T. Maas, and J. J. de Koning (2016). The influence of added mass on optimal step length in running. *International Journal of Sports Physiology and Performance 11*(7), 920–926.

Rejeski, W. J. (1985). Perceived exertion: An active or passive process? *Journal of Sport Psychology 7*(4), 371–378.

Rendi, M., A. Szabo, and T. Szabó (2008). Performance enhancement with music in rowing sprint. *The Sport Psychologist 22*(2), 175–182.

Repp, B. H. and Y.-H. Su (2013). Sensorimotor synchronization: a review of recent research (2006–2012). *Psychonomic Bulletin & Review 20*(3), 403–452.

Richardson, M. J., K. L. Marsh, and R. Schmidt (2005). Effects of visual and verbal interaction on unintentional interpersonal coordination. *Journal of Experimental Psychology: Human Perception and Performance 31*(1), 62–79.

Rochester, L., V. Hetherington, D. Jones, A. Nieuwboer, A.-M. Willems, G. Kwakkel, and E. Van Wegen (2005). The effect of external rhythmic cues (auditory and visual) on walking during a functional task in homes of people with parkinson's disease. *Archives of Physical Medicine and Rehabilitation 86*(5), 999–1006.

Roerdink, M., P. J. Bank, C. Peper, and P. J. Beek (2011). Walking to the beat of different drums: practical implications for the use of acoustic rhythms in gait rehabilitation. *Gait & Posture 33*(4), 690–694.

Rossignol, S. and G. M. Jones (1976). Audio-spinal influence in man studied by the h-reflex and its possible role on rhythmic movements synchronized to sound. *Electroencephalography and Clinical Neurophysiology 41*(1), 83–92.

Salimpoor, V. N., D. H. Zald, R. J. Zatorre, A. Dagher, and A. R. McIntosh (2015). Predictions and the brain: how musical sounds become rewarding. *Trends in Cognitive Sciences 19*(2), 86–91.

Särkämö, T., M. Tervaniemi, S. Laitinen, A. Forsblom, S. Soinila, M. Mikkonen, T. Autti, H. M. Silvennoinen, J. Erkkilä, M. Laine, et al. (2008). Music listening enhances cognitive recovery and mood after middle cerebral artery stroke. *Brain 131*(3), 866–876.

Schaefer, R. S. and K. Overy (2015). Motor responses to a steady beat. *Annals of the New York Academy of Sciences 1337*(1), 40–44.

Schmidt, R. and M. Richardson (2008). Dynamics of interpersonal coordination. In A. Fuchs and V. Jirsa (Eds.), *Coordination: Neural, Behavioral and Social Dynamics. Understanding Complex Systems.*, pp. 281–308. Springer, Berlin, Heidelberg.

Schmidt, R., M. J. Richardson, C. Arsenault, and B. Galantucci (2007). Visual tracking and entrainment to an environmental rhythm. *Journal of Experimental Psychology: Human Perception and Performance 33*(4), 860–870.

Shaulov, N. and D. Lufi (2009). Music and light during indoor cycling. *Perceptual and Motor Skills 108*(2), 597–607.

Simpson, S. D. and C. I. Karageorghis (2006). The effects of synchronous music on 400-m sprint performance. *Journal of Sports Sciences 24*(10), 1095–1102.

Smoll, F. L. and R. W. Schutz (1982). Accuracy of rhythmic motor behavior in response to preferred and nonpreferred tempos. *Journal of Human Movement Studies 8*(3), 123–138.

Stephan, K., M. Thaut, G. Wunderlich, W. Schicks, B. Tian, L. Tellmann, T. Schmitz, H. Herzog, G. McIntosh, R. Seitz, and V. Hömberg (2002). Conscious and subconscious sensorimotor synchronization - prefrontal cortex and the influence of awareness. *NeuroImage 15*, 345–352.

Strogatz, S. H. (1994). *Nonlinear dynamics and chaos: with applications to physics, biology, chemistry, and engineering*. Reading, MA: Addison-Wesley.

Stupacher, J., M. J. Hove, C. Novembre, S. Schütz-Bosbach, and P. E. Keller (2013). Musical groove modulates motor cortex excitability: A TMS investigation. *Brain and Cognition 82*(2), 127–136.

Styns, F., L. van Noorden, D. Moelants, and M. Leman (2007). Walking on music. *Human Movement Science 26*, 769–785.

Taunton, J. E., M. B. Ryan, D. Clement, D. C. McKenzie, D. Lloyd-Smith, and B. Zumbo (2002). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine 36*(2), 95–101.

Tenenbaum, G. (2005). The study of perceived and sustained effort: Concepts, research findings and new directions. In H. D, D. J, and L. R (Eds.), *Handbook of research in applied sport and exercise psychology: international perspectives*, pp. 335–349. Morgantown, WV: Fitness Information Technology.

Tenenbaum, G. and J. C. Hutchinson (2007). A social-cognitive perspective of perceived and sustained effort. In G. Tenenbaum and R. C. Eklund (Eds.), *Handbook of sport psychology, 3rd ed*, pp. 560–577. Hoboken, NJ, US: John Wiley & Sons Inc.

Terry, P. C., C. I. Karageorghis, A. M. Saha, and S. D'Auria (2012). Effects of synchronous music on treadmill running among elite triathletes. *Journal of Science and Medicine in Sport 15*, 52–57.

Thaut, M. H., G. C. McIntosh, and V. Hoemberg (2014). Neurobiological foundations of neurologic music therapy: rhythmic entrainment and the motor system. *Frontiers in Psychology 5*(1185), doi:10.3389/fpsyg.2014.01185.

Van Dyck, E., D. Moelants, M. Demey, A. Deweppe, P. Coussement, and M. Leman (2013). The impact of the bass drum on human dance movement. *Music Perception: An Interdisciplinary Journal 30*(4), 349–359.

Van Dyck, E., B. Moens, J. Buhmann, M. Demey, E. Coorevits, S. D. Bella, and M. Leman (2015). Spontaneous entrainment of running cadence to music tempo. *Sports medicine-open 1*(15), doi:10.1186/s40798–015–0025–9.

van Gent, B. R., D. D. Siem, M. van Middelkoop, T. A. van Os, S. S. Bierma-Zeinstra, and B. B. Koes (2007). Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *British Journal of Sports Medicine 41*, doi:10.1136/bjsm.2006.033548.

van Noorden, L. and D. Moelants (1999). Resonance in the perception of musical pulse. *Journal of New Music Research 28*(1), 43–66.

van Ulzen, N. R., C. J. C. Lamoth, A. Daffertshofer, G. R. Semin, and P. J. Beek (2008, February). Characteristics of instructed and uninstructed interpersonal coordination while walking side-by-side. *Neurosci Lett 432*(2), 88–93.

Varewyck, M., J.-P. Martens, and M. Leman (2013). Musical meter classification with beat synchronous acoustic features, DFT-based metrical features and support vector machines. *Journal of New Music Research 42*(3), 267–282.

Von Holst, E. (1973). Relative coordination as a phenomenon and as a method of analysis of central nervous system function. In *The Behavioural Physiology of Animals and Man: The Collected Papers of Erich Von Holst, Volume 1*, Volume 1, pp. 33–135. Coral Gables: University of Miami Press.

Waterhouse, J., P. Hudson, and B. Edwards (2010). Effects of music tempo upon submaximal cycling performance. *Scandinavian Journal of Medicine & Science in Sports 20*(4), 662–669.

Wellenkotter, J., T. Kernozek, S. Meardon, and T. Suchomel (2014). The effects of running cadence manipulation on plantar loading in healthy runners. *International Journal of Sports Medicine 35*(09), 779–784.

Williams, D. M. (2008). Exercise, affect, and adherence: an integrated model and a case for self-paced exercise. *Journal of Sport and Exercise Psychology 30*(5), 471–496.

Yamashita, S., K. Iwai, T. Akimoto, J. Sugawara, and I. Kono (2006). Effects of music during exercise on rpe, heart rate and the autonomic nervous system. *Journal of Sports Medicine and Physical Fitness 46*(3), 425–430.

Zarrugh, M. Y., F. N. Todd, and H. J. Ralston (1974). Optimization of energy expenditure during level walking. *European Journal of Applied Physiology and Occupational Physiology 33*(4), 293–306.