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Vakgroep Kunst-, Muziek- en Theaterwetenschappen

Music-based biofeedback for sports applications

Valerio Lorenzoni

Proefschrift voorgelegd tot het behalen van
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Theaterwetenschappen

Promotor:	Prof. Dr. Marc Leman
Doctoraatsbegeleidingscommissie:	Prof. Dr. Pieter-Jan Maes Prof. Dr. Tijl De Bie
Examencommissie:	Prof. Dr. Marc Boone (voorzitter) Prof. Dr. Federico Avanzini Prof. Dr. Leon van Noorden Prof. Dr. Veerle Segers Dr. Denis Amelynck

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

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A long journey...
and many people to thank

Music and sound have always been my passion and have constituted the backbone of my academic and working career. My bachelor thesis back in Rome dealt with the comparison of a real saxophone bore with a computer simulation of the same geometry, based on Kirkhhoff's integrals, which could be used for the production of physical-based music synthesizers. When I started my master in aerodynamics at Delft University I decided to follow a course in acoustics, because something was calling from that side. That is how my adventure in the world of aeroacoustics began. The latter is the scientific discipline, formalized by sir Lighthill in the 1950's, which explains how air flow and turbulence generate sound. This applies to airplane jet noise, wind turbine noise...but also to sound generation in wind instruments. I found this extremely fascinating!

While working on fluid-structure interaction noise problems at Delft University, I decided to perform an aerodynamic experiment to measure the airflow inside a saxophone mouthpiece to better understand the mechanisms of sound generation inside the saxophone. I would like to thank the head of the aerodynamic department Prof. Fulvio Scarano, who always believed in me and let me "play" with the expensive system for aerodynamic measurements (PIV). This experiment led to one of my first publications about the aerodynamics inside a saxophone mouthpiece in playing conditions. That would not have been possible without the help of Prof. Mico Hirschberg, a reference figure in the field of aeroacoustics in Europe, who kept repeating me it was a crazy idea, but helped me out examining the data and writing the paper.

A few months later, I got a job in Denmark at Siemens Wind Power as wind turbine engineer. The job was relatively new to me, therefore challenging and stimulating. Although still working on aeroacoustics of wind turbines, I felt that my job was not only to reduce noise but to "produce sounds" and that I needed a more artistic job to put me in contact with music. The results of a Birkman test confirmed that the jobs that would have matched my personality were: musician, radio speaker or niche researcher (i.e. someone fully focused on something really specific). Although this was not really new to me, it confirmed my thoughts and I decided to quit my job at Siemens after about 4 years, and try to be a musician.

However, musician life is harder than most people think and the small engineer inside me kept calling me and kept me working on something scientific but still related to music: 3D printed saxophone mouthpieces, together with the faculty of industrial design of Delft University. This collaboration led to the production of some nice mouthpiece prototypes that some professional musicians are nowadays still using, and to conference publications.

A breakthrough in my research process towards an artistic/technological profession was offered by the first Arduino Jam I joined in 2015 in Ghent, organised by Toon Nelissen. It was a pure combination of technology, programming, and music making. I decided that that had to become my work. While I was looking for jobs in Belgium that allowed me explore music and sound and to use my scientific/technological background, I found IPEM on the web and I was fascinated by their projects and interesting research activities. I immediately emailed Prof. Marc Leman asking if there was an open position for me at IPEM. He invited me for an interview and in that meeting I found the job I was looking for in the last years.

I would like to thank you Marc for making me a member of the IPEM team and having faith in me being a decent musicology researcher, not having a musicology background. I would also like to thank all of my IPEM colleagues, in particular Joren Six and Bart Moens. I bored you guys with my all my questions about programming and I used lots of your time. My background was far from computer science, but you were always open to offer me your help in small and bigger programming and technological problems. Many thanks to the members of my doctoral committee: to Prof. Pieter-Jan Maes, for the many discussions on all the topics of my PhD and to Prof. Tijl De Bie, for the constructive talks and for introducing me to the world of machine learning. I would also like to thank the people of the Department of Movement and Sports Sciences of Gent University for the pleasant and fruitful collaboration, especially: Pieter van den Berghe, Joeri Gaerlo, Rud Derie and Prof. Dirk De Clercq.

The work at IPEM is a complete team work. I would like to thank Jeska Buhmann, Edith Van Dyck and Kelsey Onderdijk, for your positive help in statistical problem and the attention for details that I sometimes underestimated in my work, taken by euphoria. Many thanks to Ivan Scheepers, for helping out with anything that needed to be developed, tested or fixed, also beyond work related topics. A big thank goes to all the rest of my colleagues at IPEM for the pleasant working environment you created in these years. Although outside the official working environment, I would like to thank all the members of my band L'Chaim that after 12 years became a kind of family to me. You keep my desire to play music always burning and you make me constantly discover and experience new aspects of the musical world.

Ghent, August 2019
Valerio Lorenzoni

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List of Acronyms

AI	Artificial Intelligence
ANOVA	Analysis of Variance
APTA	Axial Peak Tibial Acceleration
BMRI	Brunel Music Rating Inventory
BPM	Beats Per Minute
EMC	Embodied Music Cognition
IMU	Inertial Measurement Unit
IPEM	Institute for Psychoacoustics and Electronic Music
JND	Just Noticeable Difference
MOCAP	Motion Capture
KS	Kolmogorov-Smirnov
PACES	Physical Activity Enjoyment Scale
PD	Parkinson's Disease
RMS	Root Mean Square
RMSE	Root Mean Square Error
RPE	Rating of Perceived Exertion
SPM	Steps Per Minute

English Summary

This dissertation describes the development and validation experiments of music-based biofeedback systems for different sports applications. The main goal of such systems is to improve sport technique for injury prevention and performance enhancement by employing the power of music.

The first chapter introduces the importance of sports in human life and the current technological devices that can help people during physical activity. Injuries can be minimized by making people aware of their technique or physical state by the use of real-time feedback systems. We propose solutions based on music and alteration of it as feedback. The theoretical background that justifies the use of music as feedback is described. This relies on the theory of embodied music interaction which formalizes the invisible link between music listening and corporeal action. The implemented feedback strategies rely on the concept of reinforcement learning which is a key principle for human learning and is lately receiving particular attention in the field of robotics and AI. The use of music as biofeedback is also supported by theoretical models that pinpoint the advantages of using music compared to standard sonification techniques and hinge on intrinsic reward mechanisms of music.

Specifically, the reward mechanisms we used in the presented works can be classified into two categories: music-to-movement synchronization (in chapters 2 and 6) and music audio quality or consonance (in chapters 3, 4, and 5). These constitute the techniques we used to stimulate movement alterations, independently of the sports applications.

The main research question we wanted to answer was: *are our music based biofeedback systems able to induce movement technique changes/improvements without providing specific instructions?* To answer this question we performed several experiments dealing with different sports. In particular, we took into consideration *running* in chapters 2, 3, and 4, *weightlifting* in chapter 5, and *cycling* in chapter 6.

In chapter 2 we altered the music to movement synchronization parameters and looked at the effect of this on the foot strike landing impact of runners. Participants (N=29) were requested to run five trials of 3' and 30" on five different randomized conditions. Specifically, one condition completely without music, two asynchronous music conditions: *Minus 30%* and *Plus 30%* in which the music was played in a tempo respectively 30% lower and higher than the initial measured running cadence and two synchronization conditions: *Tempo-entrained Sync* and *Phase-locked Sync*. In the first one the tempo of the music was matched to the ca-

dence of the runner, while in the second one foot strikes were continuously aligned in tempo and phase with the music beats. Results showed that (a)synchronization of the music with the runners' foot strikes does not have direct influence on the impact level. However, music onset was observed to cause an impact level increase in all conditions with music, compared to the condition without music. This work can be considered as preliminary study for the experiments of chapters 3 and 4 and the results justified the use of synchronous music in the later tests.

Chapter 3 describes the development and validation of a music-based biofeedback system based on audio quality alterations for modification of running parameters. The experiments of section 3.2 were conducted on panels of participants to select the most pleasurable and most discernible music alteration (among white and pink noise, volume variations and sampling rate alterations). The best performing music alteration was found to be the addition of pink noise on top of a baseline music track. Further experiments were carried out in running conditions to evaluate the just noticeable difference (JND) for noise discretization. Validation of the system consisted in alterations of the runners' steps per minute (SPM) compared to their reference running cadence on tread-mill running. In this case, participants (N = 13) were asked to run during four experimental conditions. The first one served as baseline for reference measurement and warm-up. Successively, participants received music-based biofeedback aiming at increasing SPM by 15%. This was compared with verbal instructions. In a second phase the target SPM was varied towards positive and negative variations of SPM to explore the range of effectiveness of the developed feedback strategy. Results in this case showed that the biofeedback system was able to increase running cadence up to 7% in a clear and non-disturbing way.

The music-based biofeedback developed in the work of chapter 3 was further used in the experiment of chapter 4 aiming at reduction of foot strike impact loading in over-ground running. The latter parameter is directly linked to runners' lower limb injuries. Experiments were carried out at the Department of Movement and Sports Sciences of Ghent University on 10 participants running sessions of 20 min. The real-time biofeedback was able to decrease participants' average tibial shock by 3 g or 27% without guided instructions on gait modification. No changes in running speed nor cadence were observed due to application of the biofeedback, suggesting personalized kinematic responses for lower impact running. These findings showed the potential of such wearable biofeedback systems for self-training in natural environments.

A different kind of audio-quality-based biofeedback system was developed for improvements of weightlifting movements; experiments are described in chapter 5. In this case, participants (N=31) were invited to perform repetitions of a standard power lifting movement called *deadlift*. Participants were split into two groups: one received feedback by a trainer (N=15) and the other received music-based biofeedback (N=16), both in real-time. The movement parameters of interest in this case were, spine bending and horizontal displacement of the barbell during movement execution; both of these are important factors in the prevention of lower back injuries. These were captured using a Motion Capture (MOCAP) system and tracking markers attached on the body of the participant and on the barbell. The music-based biofeedback in this case consisted of the downsampling of a baseline music track and a change in *panning* (distribution of active speakers) of the audio surrounding system (frontal or surround). Analysis revealed that the proposed biofeedback system was able to improve movement correctness with respect to the initial movements without feedback, in a comparable way to standard feedback by the trainer, both in terms of measured parameters and qualitative judgement by participants.

The last experiment we present in this dissertation deals with cycling and how to improve synchronization of cyclists' pedaling cadence to external music. Fifteen participants took part in this experiment and were asked to carry out 5 trials of 270" each, on a stationary bike. The pedaling cadence was measured using a rotary encoder mounted on the bike crank. For each trial a different movement sonification type was added on top of a baseline music track. These consisted of, respectively: melody sequence, drum sequence, beep sequence, a no-sonification condition and a silent condition. Each trial consisted of four parts. In a first part no music and no sonification was provided (20") and in the second phase only sonification was added. In the third part of the trial (60") music was added to the movement and continuously aligned in tempo and phase with the pedalling cadence. In the fourth phase (180") music tempo was fixed and we looked at how much the cyclist was able to autonomously align with the music beat, with the different sonification strategies mentioned above. Results showed that a clear beep at one position during pedaling rotation helped participants to best align with the music beat and to keep a more constant rotation speed compared to the other sonification strategies or no sonification. Such locking between the music beat and the sonification of the pedaling could be used to steer pedaling cadence towards optimal values and is relevant for sports training and motor rehabilitation.

All the presented studies show how music and music alterations can be used to modify physical parameters in different sports disciplines. Video material to illustrate the described experiments can be found at: www.valeriolorenzoni.com/rd/ In the final chapter of this thesis (chapter 7) we summarize the main results of our studies and provide answers to our earlier posed research questions. In addition, we discuss our contributions to the research field and possible tracks for future research.

Nederlandse Samenvatting –Summary in Dutch–

Dit proefschrift behandelt zowel ontwikkelingen, als validatie-experimenten met betrekking tot muziek-gebaseerde biofeedback systemen gericht op verschillende sporttoepassingen. Het doel van dergelijke systemen is om, met oog op letselpreventie en prestatieverbetering, sporttechnieken te hervormen door gebruik te maken van de kracht van muziek.

Het eerste hoofdstuk bespreekt het belang van sport voor de mens en overloopt de reeds beschikbare technologieën ter ondersteuning van lichamelijke activiteiten. De kans op letsels kan worden geminimaliseerd door mensen bewust te maken van hun (gebrekkige) technieken of fysieke toestand aan de hand van real-time feedbacksystemen. In deze uiteenzetting stellen we oplossingen voor op basis van muziek en modulatie hiervan als feedback. Tevens wordt de theoretische achtergrond die het gebruik van muziek als feedback rechtvaardigt geduid. Dit alles is gebaseerd op de theorie van *lichamelijke interactie met muziek*, die de onzichtbare link legt tussen muzikale perceptie en lichamelijke actie formaliseert. De geïmplementeerde feedbackstrategieën steunen op het concept van versterkend leren (*reinforcement learning*), een sleutelprincipe voor het menselijk leerproces dat de laatste tijd bijzondere aandacht krijgt op het gebied van robotica en AI. Het gebruik van muziek ten opzichte van geluid als biofeedback, wordt ook ondersteund door theoretische modellen die de voordelen ervan benadrukken en verwijzen naar de intrinsieke beloningsmechanismen van muziek.

Concreet kunnen de beloningsmechanismen die we in de gepresenteerde werken bespreken, worden ingedeeld in twee categorieën: synchronisatie van muziek en beweging (in hoofdstuk 2 en 6) en geluidskwaliteit van muziek of consonantie (in hoofdstuk 3, 4 en 5). Deze beslaan de technieken die werden ingezet om aanpassingen in beweging te stimuleren, onafhankelijk van de sporttoepassing.

De hoofdonderzoeksvraag van dit proefschrift luidt als volgt: *"Zijn onze op muziek gebaseerde biofeedbacksystemen in staat veranderingen en/of verbeteringen in bewegingen aan te brengen zonder gebruik te maken van specifieke instructies?"* Om deze vraag te beantwoorden, voerden we experimenten uit in verschillende sport- domeinen. In hoofdstukken 2, 3 en 4 bespreken we onderzoek omtrent *hardlopen*, in hoofdstuk 5 behandelen we een studie over *gewichtheffen*, en *fietsen* vormt de onderzoeksfocus in hoofdstuk 6. In hoofdstuk 2 behandelen we een studie waarbij we de op beweging gebaseerde synchronisatieparameters in de muziek wijzigden en het effect van deze aanpassingen op de impact van het neerkomen van de voet bij hardlopers bestudeerden. Deelnemers (*N* = 29) werden gevraagd om vijf hardloopsessies (3' en 30" per sessie) uit te voeren, dit in verschillende gerandomiseerde condities. In één conditie was de muziek volledig afwezig, in twee condities werd de muziek asynchroon afgespeeld (*Minus 30%* en *Plus 30%;* waarbij de muziek werd gespeeld in een tempo respectievelijk 30% lager of hoger dan de aanvankelijk geregistreerde loopcadans), en in twee condities werd de muziek gesynchroniseerd met de beweging (*Tempo-entrained Sync* en *Phase-locked Sync*; in de eerste conditie werd het tempo van de muziek afgestemd op de cadans van de hardloper, in de tweede werden voetstappen tevens in fase uitgelijnd met de beats van de muziek). Uit de resultaten bleek dat (a)synchronisatie van muziek en hardloopgedrag geen directe invloed had op het impactniveau. Echter, de aanwezigheid van muziek op zich, bleek in alle omstandigheden een stijging van het impactniveau te veroorzaken in vergelijking met de condities zonder muziek. Dit onderzoek kan worden beschouwd als een voorstudie voor de experimenten besproken in hoofdstukken 3 en 4. Tevens rechtvaardigen de resultaten het gebruik van synchroon aangeboden muziek in de latere tests.

Hoofdstuk 3 behandelt de ontwikkeling en validatie van een op muziek gebaseerd biofeedbacksysteem, waarbij wijzigingen in de audiokwaliteit werden ingezet voor het aanpassen van loopparameters. De experimenten gerapporteerd in sectie 3.2 peilden bij een panel van deelnemers naar de meest plezierige en waarneembare muziekverandering (bij witte en roze ruis, volumevariaties, wijzigingen in de *sample rate*). Resultaten toonden aan dat de beste muziekverandering roze ruis was, toegevoegd bovenop een onderliggende muziektrack. Verdere hardloopexperimenten werden uitgevoerd om het net merkbare verschil (*just noticeable difference* of *JND*) voor geluidsherkenning te evalueren. Het systeem werd gevalideerd aan de hand van de veranderingen in cadans van het hardlopen (gemeten in aantal stappen per minuut, of SPM) in relatie tot de referentiecadans. In een studie werden deelnemers (*N* = 13) gevraagd om in vier condities te hardlopen. De eerste conditie diende als referentiemeting enerzijds en als warm-up anderzijds. Achtereenvolgens kregen de deelnemers op muziek gebaseerde biofeedback te horen, gericht op een SPM-toename met 15%. Het effect op het hardloopgedrag werd vergeleken met een conditie waarin mondelinge instructie werd gegeven. In een tweede fase werd het te bereiken aantal stappen per minuut positief of negatief gevarieerd om zo het bereik van de effectiviteit van de ontwikkelde feedbackstrategie te verkennen. Resultaten toonden aan dat het biofeedbacksysteem de cadans tot 7% kon verhogen, dit op een duidelijke en niet-storende manier.

De op muziek gebaseerde biofeedback, beschreven in voorgaand hoofdstuk, werd verder toegepast in het experiment belicht in hoofdstuk 4. Dit experiment is gericht op de impactafname van de belasting die gegenereerd wordt bij het neerkomen van de voet. Deze impact kan rechtstreeks in verband gebracht worden met blessures aan de onderste ledematen bij hardlopers. Het experiment werd uitgevoerd aan de Vakgroep Bewegings- en Sportwetenschappen van de Universiteit Gent, waarbij de participanten (*N* = 10) gevraagd werd om 20 minuten te hardlopen met een draagbaar biofeedbacksysteem. De real-time biofeedback bleek in staat om de gemiddelde scheenbeenschok met 3 g of 27% af te laten nemen zonder mondelinge instructies. Er werden geen veranderingen in hardloopsnelheid of cadans waargenomen als direct gevolg van de biofeedback, waarmee persoonlijke kinematische reacties worden gesuggereerd betreffende hardlopen met minder impact. Deze bevindingen tonen het potentieel aan van dergelijke draagbare biofeedbacksystemen bij individuele trainingen in natuurlijke omgevingen.

In hoofdstuk 5 beschrijven we een ander type biofeedbacksystemen, gebaseerd op audio kwaliteit. Dit systeem werd ontwikkeld voor het verbeteren van courant gebruikte bewegingen bij gewichtheffen. Voor deze studie werden deelnemers (N = 31) uitgenodigd om een standaard powerlift beweging, *deadlift* genaamd, herhaaldelijk uit te voeren. Deelnemers werden in twee groepen verdeeld: de ene groep kreeg real-time feedback van een trainer (N = 15), terwijl de andere (N = 16) real-time op muziek gebaseerde biofeedback ontving. Cruciale bewegingsparameters betroffen hier de wervelkolombuiging en horizontale verplaatsing van de lange halter tijdens de uitvoering van de bewegingen; beide zijn belangrijke factoren bij de preventie van lage rugklachten. Bewegingen werden geregistreerd door middel van digitale camera's (Qualisys Motion Capture). Deze lieten het volgen van reflecterende markers toe, die werden bevestigd aan de rug van de deelnemers en op de lange halter. De op muziek gebaseerde biofeedback bestond in dit geval uit het vervormen (*downsampling)* van een muzikale stimulus en een verandering in *panning* (distributie van actieve luidsprekers) van het audiosysteem (frontaal of surround). Analyses toonden aan dat het voorgestelde biofeedbacksysteem de nauwkeurigheid van de beweging positief kon bijregelen, te vergelijken met standaard feedback van een trainer, zowel in termen van gemeten parameters als in kwalitatieve beoordeling van de deelnemers.

In hoofdstuk 6 bespreken we een fietsexperiment waarbij gefocust wordt op de wijze waarop de synchronisatie van trapfrequentie en muziektempo kan worden geoptimaliseerd. Deelnemers (N = 15) werden gevraagd om vijf sessies (270" per sessie) op een stationaire fiets uit te voeren. De trapfrequentie werd gemeten aan de hand van roterende encoders op een fietskruk. Voor elke sessie werd een ander (op beweging gebaseerd) sonificatietype aan de muzikale stimulus toegevoegd. Deze sonificatietypes bestonden uit respectievelijk: melodiesequentie, drumsequentie, piepsequentie, een toestand zonder sonificatie en een toestand helemaal zonder geluid. Elke sessie bestond uit vier delen. In het eerste deel werd muziek noch sonificatie verschaft (20") en in het tweede deel werd alleen sonificatie toegevoegd. In het derde deel van de proef (60") werd muziek, die continu op het tempo en fase van de trapfrequentie uitgelijnd werd, toegevoegd. Tenslotte, werd in het vierde deel (180") het tempo van de muziek constant gehouden en gingen we na in hoeverre de fietser in staat was om op autonome wijze zijn/haar trapfrequentie op de beat van de muziek af te stemmen, dit aan de hand van de verschillende bovengenoemde sonificatiestrategieën. De resultaten toonden aan dat een duidelijke toon op een specifieke positie tijdens de rotatie van de pedalen de fietsers ondersteunde om zich op de beat van de muziek te richten en een meer constante rotatiesnelheid te behouden in vergelijking tot de andere sonificatiestrategieën (of bij afwezigheid van sonificatie). Een dergelijke koppeling tussen de beat van de muziek en sonificatie van de pedalen kan gebruikt worden om de trapfrequentie op optimale wijze bij te sturen. Het kunnen bijsturen van de trapfrequentie is zeer relevant in het licht van sporttraining en motorische revalidatie.

De gepresenteerde studies tonen aan hoe muziek en meer specifiek modulaties in de muziek kunnen worden aangewend om fysieke parameters van sporters in verschillende disciplines te wijzigen en/of te optimaliseren.
Videomateriaal ter illustratie van de beschreven experimenten is te vinden op: www.valeriolorenzoni.com/rd/

In het laatste hoofdstuk van dit proefschrift (hoofdstuk 7) bespreken we de resultaten van onze studies aan de hand van de eerder aangeleverde onderzoeksvragen. Ten slotte behandelen we onze bijdragen aan het onderzoeksveld en lichten we een mogelijke parcours voor toekomstig onderzoek toe.

List of Publications

Publications in international journals

Lorenzoni, V., Van den Berghe, P., Maes, P. J., De Bie, T., De Clercq, D. and Leman, M. (2018). Design and validation of an auditory biofeedback system for modification of running parameters. *Journal on Multimodal User Interfaces*

Lorenzoni, V., De Bie, T., Marchant, T., van Dyck, E. and Leman, M. (2019) The effect of (a)synchronous music on runners' lower leg impact loading. *Musicae Scientiae*

Lorenzoni, V., Staley, J., Marchant, T., Onderdijk, K. E., Maes, P. J. and Leman, M. (2019) The sonic instructor: a music-based biofeedback system for improving weightlifting technique. *PLOS One*

Van den Berghe, P., Lorenzoni, V., Derie, R., Six, J., Gerlo, J., Leman, M. and De Clercq, D. (2019).Tibial shock reduction by means of music-based biofeedback in over-ground running: proof-of-concept. Submitted to *Scientific Reports*. Shared first authorship.

Maes, P. J., Lorenzoni, V. and Six, J. (2018). The SoundBike: musical sonification strategies to enhance cyclists' spontaneous synchronization to external music. *Journal on Multimodal User Interfaces*

Maes, P. J., Lorenzoni, V., Moens, B., Six, J., Bressan, F., Schepers, I., and Leman, M. (2018). Embodied, participatory sense-making in digitally-augmented music practices: theoretical principles and the artistic case "Sound-Bikes". *Critical Arts*

Publications in international conferences

Lorenzoni, V., Van Dyck, E., and Leman, M. (2017). Effect of music synchronization on runners' foot strike impact. In *Proceedings of the 25th Anniversary Conference of the European Society for the Cognitive Sciences of Music, ESCOM, 2017, Ghent, Belgium.*

Lorenzoni, V., Maes, P.J., Van den Berghe, P., De Clercq, D., De Bie, T., and Leman, M. (2018). A biofeedback music-sonification system for gait retraining. *Proceedings of the 5th international conference on movement and computing, MOCO 2018, Genova, Italy.*

Buhmann, J., Moens, B., Lorenzoni, V., and 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.*

Patents

Patent pending. Low impact running. The patent relates to methods and systems which support a runner in gait retraining. Co-inventors: Pieter van den Berghe, Joeri Gerlo, Joren Six, Valerio Lorenzoni, Dirk De Clerq and Marc Leman. Application number PCT/EP2019/066738, filed 25/06/2019

1
Introduction

1.1 General context

The strict relationship between music and physical activity is well known and constitutes the foundation of this work. Music has accompanied human activities since prehistorical times (Conard et al., 2009) and still nowadays it is a fundamental element of our everyday life, even more than we are aware of. Music accompanies recreational events (parties, clubbing, festivity, etc.) but also working activities both indoor and outdoor. Thanks to technological improvements, seeing people walking, jogging or biking with portable music players has become extremely common (Moens, 2018). The benefits of listening to music while performing sports have been reported by several authors (see references in Van Dyck et al., 2015). Dopamine release during music listening makes it a powerful, healthy and legal (except in sports competitions, Van Dyck and Leman, 2016) drug. This thesis deals with different systems designed to help people during sports activities by exploiting the power of music. Specifically, we used embodied reward mechanisms based upon music to alter/improve sports movement parameters for injury prevention and performance enhancement.

This chapter is structured as follows: in the first section (1.1) we explain the importance and benefits of sports in human life together with the associated risks. The technological developments and some of the technological systems that opened the possibility for creating movement awareness during motor activities are successively presented. We then define the research questions that led to the development of the proposed systems. In the second section (1.2), the theoretical background behind the development of the presented systems is explained with special emphasis on the concept of reinforcement learning. Section 1.3 is dedicated to the experimental methodology we used for designing and validating the proposed feedback systems. The final section (1.4) provides a general outline of the thesis.

1.1.1 Sports and health

Physical activity is a fundamental element for health and wellbeing with positive effects at both physical and mental levels. Participation in sports is associated with better quality of life and reduced risk of several diseases (Khan et al., 2012). Sports activities have been shown to improve cardiovascular health, reduce body fat and increase muscular strength, endurance, and power (Warburton et al., 2006). Beyond physical benefits, sports are also associated with several psychological and emotional benefits as they are able to relieve stress, anxiety, depression and anger (Taylor et al., 1985). Furthermore, there is a strong relationship between the development of positive self-esteem, due to testing of self in a context of sports competition. Physical activities also contribute to social development of athletes, prosocial behaviour, fair play and sports personship and personal responsibility (Wankel and Berger, 1990).

According to the Eurobarometer survey on sport and physical activity (The European Commission, 2018), in 2018 in Europe, more than half of men and women between the age of 15 and 24 years exercised or played sports with at least some regularity. The number of health and fitness clubs has steadily increased in the last years to more than 50.000 and the number of club members to over 50 million. Recent sports activities as CrossFit and Bootcamp are growing popular both as sports practices and as recreational and social activities.

Engaging in sports activities has numerous health benefits, but also carries the risk of injury (Maffulli et al., 2010). An increasing number of children undergo intensive training routines and high level competition from an early age. Although physical training may foster health benefits, many are injured as a result of it. According to the European Injury Data Base (EuroSafe, 2016) about 4.5 million people aged 15 years and older have to be treated in EU hospitals for sports injury (see Kisser and Bauer, 2010). Team ball sports account for 40% of all hospital treated sports injuries, with football (soccer) accounting for the most. Two thirds of the injuries affect men, although with huge differences in the various types of sports. If we consider recreational runners, who are steadily training and who participate in a long distance run every now and then, the overall yearly incident rate for running injuries varies between 37 and 56%. Most running injuries are lower extremity injuries, with a predominance for the knee (Van Mechelen, 1992).

Figure 1.1: Outdoor bootcamp session. Image from Body Based (2019), www.bodybased.nl, cit. "The body moves, the mind grooves"

To prevent sport-related injuries physiotherapists and doctors commonly stress the importance of early recognition of symptoms of overuse and provision of training guidelines. This dissertation focuses on systems able to continuously monitor the physical state and make people aware of their current movements for injury minimization and technique learning/improvements.

1.1.2 Technology in sports

Exponential progress in the field of electronics in the last decades, has led to miniaturization of different kinds of sensors and processors. Technological systems to facilitate human activities have become available to many people, e.g. assisted or smart cars, smart houses and programmable households. In 2018 the number of people using smartphones exceeded 2.5 billion, which corresponds to over 30% of the world population. Most smartphones have embedded sensors and associated microprocessors able to measure environmental and physiological parameters. This indicates that the possibility now exists to monitor and track human activity with precision throughout the day; typical examples are apps counting number of steps or travelled distance per day. Wearable-technologies, i.e. smart electronic devices that can be incorporated in clothes and can be worn as accessories, are becoming increasingly popular (Sawka and Friedl, 2017) (see https://www.wearable-technologies.com for the latest applications). One example is the smartwatch which nowadays still represents the most popular of wearable devices.

In the field of sports, it is of increasing interest to monitor performances of athletes during both training and competitions. Noticeable investments have been made by clubs and federations in this direction. Spending varies with the type

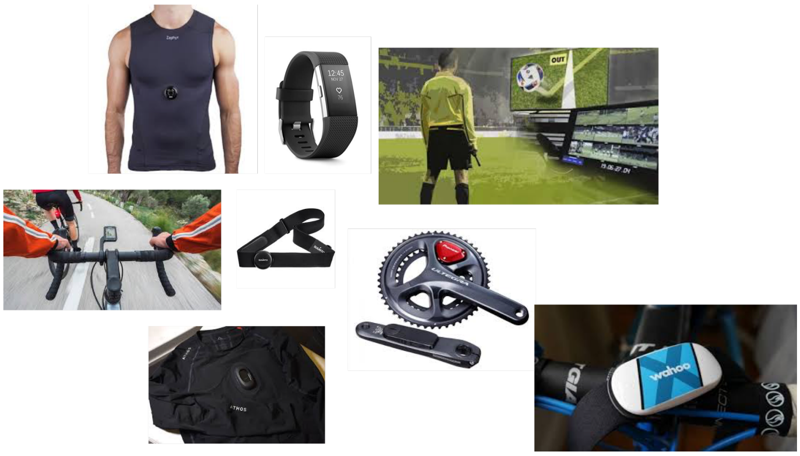

Figure 1.2: Novel technological devices currently used in sports

of sports, with soccer receiving 43% of the global share, American football 13%, baseball 12%, Formula 1 7% and basketball 6% in 2018 (MIS, 2019). The developed technological systems are used to control kinematic parameters as speed, accelerations, position as well as physiological parameters like heart rate, heart rate variability, sweat analysis, hydration and breathing rate.

A review on the use of wearable systems in sports is provided by Peake et al. (2018) and Adesida et al. (2019). Wearable sensors integrated into helmet linings and mouth guards have been used in American football to monitor concussions by measuring linear and angular head accelerations upon impact. In volleyball, the VERT inertial measurement unit (IMU) system has been used to quantify jump height accurately. KINEXON sensors are used in sports such as basketball to measure player acceleration while the NADI yoga pants employ a combination of motion sensors and haptic feedback to guide yoga technique. In the cycling world, new products are continuously being developed such as smart helmets, crank power meters, smart lights, apps and dedicated computers (see more at https://www.techradar.com/news/best-cycling-tech). Other examples of wearable systems in sports are the smart belts by SUUNTO for heart rate measurements also for swimming, the performance systems by ZEPHYR and the GPS Player Tracking and Performance Analysis by APEX. The wearable bracelet FITBIT introduced in 2007 has won several awards in the health and wellness category. It allows tracking of daily activity, exercise, sleep, nutrition, and weight and provides indications of the physical status. Some of the mentioned technological devices are presented in Figure 1.2

1.1.3 Problem statement and hypotheses

Most of the current technological systems in sports applications are prevalently used as monitoring tools. Feedback to the subjects is often provided by experienced trainers, in a posterior analysis phase. However, availability of the latter is commonly limited to sports facilities that employ such trainers, it can be costly and there is often high variability in teaching technique among instructors (Adesida et al., 2019). We believe that performances and movement technique in sports activities can be improved by providing continuous auditory feedback and by exploiting the psychophysical effects of music.

Recent technological developments have opened the possibility to provide such feedback in real-time, providing monitoring and information in a continuous way during physical activity (Sawka and Friedl, 2017). Biofeedback systems encompass a range of technological systems able to directly provide indications about physiological parameters and have been used in the domains of sports (Onate et al., 2001) and motor rehabilitation (Tate and Milner, 2016; Isakov, 2007). These are able to provide information about physiological or biomechanical parameters that would otherwise be unknown (Giggins et al., 2013). Biofeedback can be presented via visual displays, acoustics, or vibrotactile feedback. Recent applications are starting to make use of biofeedback in VR environments (Repetto et al., 2009).

However, current biofeedback systems mostly rely on "alarm-like" visual or auditory displays when the measured parameters exceed safety threshold values. These can be perceived as disturbing by practitioners and are not suited for long term (re-)training sessions.

In this dissertation, we explore a new class of solutions. Solutions suited for self-training practices that rely on music and music alterations to indicate correctness of the movements in real-time. The idea is to create systems able to steer athletes to the correct technique in an intuitive and rewarding manner. The aim is to let the subjects discover movement improvements by themselves, through coupling with musical characteristics, without the need for continuous inputs by the trainer.

The overall question we wanted to answer in developing these systems was: *are our music-based biofeedback systems able to induce movement technique changes/improvements without providing explicit instructions to the subjects?* To answer this question we tested the systems on panels of subjects and compared the performance to the subjects' initial performance values. The target movement parameters were fixed to established prevention standards or performance goals. The physical modifications were relative to the subject's initial performance and the approach was tailored to the participants.

The sports we took into consideration in the present work are: running, biking and weightlifting. These are three increasingly common sports with over 50 million recreational runners only in Europe in 2015 (Scheerder et al., 2015) and over 50 million European citizens cycling everyday (The European Commission, 2013). On the one hand, this allowed a relatively easy participants recruitment process and, on the other hand, results might have implications on a large scale. In particular, we looked at the efficacy of the developed systems to modify steps-per-minute (SPM) (see chapter 3) and lower leg impact loading for runners (chapters 2 and 4). For bikers we looked at how we could alter synchronization of pedalling cadence to music and if we could alter this by superposition of additional music layers through active musical contribution (chapter 6). In the weightlifting experiment of chapter 5 we looked at correctness of spine curvature and barbell path as these parameters are strictly related to injury prevention.

Secondary research questions differed depending on the specific applications. In chapters 3 and 5, when looking at movement improvements, we compared the performances of our system directly with standard instructions by a trainer. The underlying question in this case was: *Can these systems be used by individuals who are eager to learn or improve their technique but do not have access to sports facilities or to trainers? And how do they compare with standard training methods?*

A general question that covered the whole process is: *are these systems effective for different sports or physical activities?* And finally, since we are using systems that employ the positive characteristics of music, we also investigated: *are these systems pleasurable for the users and do participants find them more motivating than standard learning techniques?*

The answers to these questions constitute the body of this dissertation. We hypothesized that music-based biofeedback based on reward is able to improve sports performances and that this occurs in a stimulating and self-discovering way. The design of the feedback strategies has been a fundamental aspect in the evolution of this work. The biggest challenge in the design of such biofeedback is that a systematic approach is needed to choose among different sonification strategies (Bevilacqua et al., 2016). The design of the current systems was based on theoretical considerations and empirical testing. Each application required specific tests and tuning of the system to improve effectiveness and usability by the participants.

1.2 Theoretical framework

This section describes the motivation behind the choice of our specific feedback strategies. More specifically, what are the reasons for using music and what are the advantages of music with respect to other feedback strategies.

1.2.1 Embodied music cognition

Music is a highly embodied phenomenon in the sense that music listening is often associated with motor activity. The music listener does not only passively receive the musical input but engages in a closed interacting loop with the musical environment. Musical action and perception are reciprocal processes that fuel this loop.

The theory of embodied music cognition (EMC) has been formalized by Leman (2007) and Godøy and Leman (2010) and has been supported by experimental evidences (Repp, 2002; Leaver et al., 2009; Eitan and Granot, 2006; Phillips-Silver and Trainor, 2005, 2007). The embodied viewpoint holds that bodily involvement shapes the way people perceive and give meaning to the music itself. People commonly construct models of states of the surrounding world using proprioceptive and exteroceptive corporeal mediators based on prediction and previous experiences (Picard and Friston, 2014). In this perspective, music can be seen as the result of such construction process. During the act of listening, for example, we construct models of a condition (or state) that could have generated the sonic patterns. In this context, a shift occurs from the classical cognition in perception to cognition in interaction with the music patterns. The interaction is based on models which are constructed based on the coupling of perception and action, explained by the theory of event coding (TEC) (Hommel, 2015). In essence, the theory states that the planning or execution of an action, and the mere perception of the (multi-)sensory consequences of that action, are similarly represented (coded) in the brain, thereby recruiting both sensory and motor brain areas. Important in this theory is that the integration of motor and sensory representations leads to internal models of the relationship between the body and the external environment, which can contain inverse and forward components (Maes et al., 2014). Figure 1.3 by Amelynck (2014) shows the basic sensory-motor scheme of embodied music cognition.

The figure describes the interaction between an agent and the environment. When the agent decides to perform an action (e.g. music playing or dance movement) this relies on an existing repertoire (1) to execute the action (2). During this process a copy of the action and a prediction of the outcome of the action are made (3) and compared (4) with the actual execution (6) and the sensed outcome of the action (5). To minimize the prediction error, the motor pattern is adjusted according to two mechanisms: sensory-motor loop and the action-perception loop (8). The sensory-motor loop (7) is a low-level circuit where the motor activity is basically driven by sensory inputs from the environment. In contrast, the action-perception loop (8) is responsible for prediction and for issues that involve musical intentions. Performed actions cause changes in the environment that are perceived and lead to the processing and adjustment of further actions in a loop.

The embodied music cognition theory is receiving large attention in the field

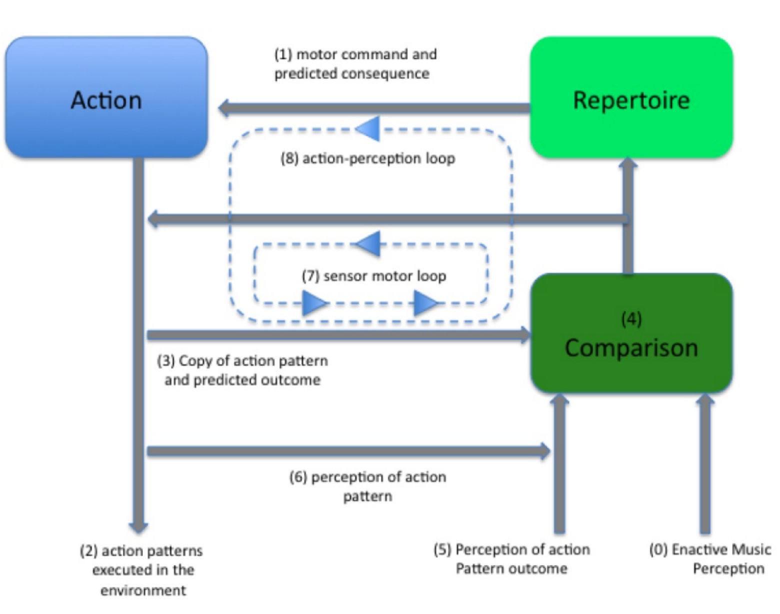

Figure 1.3: Basic scheme of embodied music cognition

of musicology, as well as in other fields such as music education, well-being, rehabilitation and sports (Cappuccio, 2015; Karageorghis et al., 2017). The systems presented in this thesis are based on the strict coupling between music features (specifically audio quality and synchronization) and body responses, following a prediction-error-minimization process. The following theoretical model aims at describing how music can be used as feedback strategy and why it is able to outperform standard auditory feedback strategies.

1.2.2 3mo model

In order to regulate and control physiological processes and physical motion in (most) optimal ways, one can typically rely on feedback strategies. Feedback may occur in many forms and types. For instance, feedback can be naturally available through a person's sensory system (i.e. task-intrinsic feedback), as well as be provided via an external source, such as a coach or technological system (i.e. augmented feedback). Within this category of augmented feedback, feedback may either be related to the performance outcome (i.e. knowledge of result) or to specific movement characteristics that lead to that outcome (i.e. knowledge of performance) (Sharma et al., 2016). In addition, augmented feedback may be provided via the different sensory modalities, typically through visual, auditory, or haptic feedback (Sigrist et al., 2013).

Real-time auditory feedback of physiological and physical information based on sound signals, often termed “sonification” , has been proven particularly effective in the context of sports performance and motor rehabilitation (Bevilacqua et al., 2016; Dubus and Bresin, 2013). The term sonification is commonly defined as the transfer of data, and data relationships, into non-speech audio for the purpose of communication and interpretation (Kramer et al., 2010; Hermann et al., 2011).

Auditory feedback has some important advantages compared to visual feedback. For instance, auditory feedback allows to keep better focus and attention to the task at hand (i.e. less distracting). This approach requires that the learner has an explicit representation of the target behavior, i.e. the goal. Sonification then functions as mere information carrier, allowing people to monitor their behavior, compare it to the target behavior, and adapt their behavior if it deviates from the target in a cognitive manner. As indicated by Leake and Ram (1995), this process is guided by reasoning and attention mechanisms and may therefore not always be the most appropriate strategy.

In their theoretical work, Maes et al. (2016) argue that the use of music as feedback offers advantages compared to standard cognitive sonification approaches. The reasoning is structured according to three main functions of music and musical biofeedback: the power of music to motivate physical activity (‘motivate’), the ability of musical biofeedback to monitor physiological and motor processes (‘monitor’), and the potential to use music to modify (i.e. optimize) these processes (‘modify’). These three core abilities represent the basis of the so-called ‘3Mo model’.

The motivational qualities of music during physical activities have been reported by several authors. Music listening can distract from fatigue (Yamashita et al., 2006; Bood et al., 2013), improve mood state (Shaulov and Lufi, 2009; Terry et al., 2012) and even boost performance (Rendi et al., 2008; Edworthy and Waring, 2006). These effects can be explained as a combination of two neurophysiological mechanisms: arousal and motor resonance. Arousal is generated in response to salient sensory events and emotional reactivity. There is large research evidence showing that music has an effect on the limbic system, which is considered to be a part of the brain strictly linked to emotions (Blood and Zatorre, 2001). Motor resonances are instead considered as an automatic activation of motor regions inside the brain (Maes et al., 2014) in response to music, due to the coupling of perception and action (Schütz-Bosbach and Prinz, 2007).

As monitoring tool, music offers advantages compared to pure sonification as it comprises multiple rhythmic and harmonic layers. The latter properties allow alignment of different muscles and body parts in a more complex and pleasurable way than single movement sonification. Examples are presented by Naveda and

Leman (2010). Coordinated behavior can thus be sonified by means of different interacting music layers.

A third function pertains to the ability of music to reliably modify physiological processes and motor behavior toward specific goals through intrinsic reward properties. The reward is based on principles related to brainstem responses and sensory-motor predictive processing that emerge by only listening to music. These mechanisms are related to prediction and expectation fulfilment (Salimpoor et al., 2015). While common feedback approaches are based on the knowledge of the specific target behavior, the 3mo model proposes and focuses on an alternative approach to behavioral modification that does not rely on self-monitoring. In other words it does not require the learner to have an explicit representation, neither of the own behavior nor of the target behavior. Instead of relying on such explicit representations, learning and adaptation becomes reward-based. The human tendency towards reward, in this case represented by music consonance or synchronization, when linked to specific movement patterns, can be used to alter motor behavior drawing upon basic principles from the reinforcement learning paradigm.

1.2.3 Reinforcement learning

In the last decades, due to the booming of artificial intelligence and machine learning, the concept of reinforcement learning has returned in vogue, leading to a remarkable interdisciplinary confluence between computer science, neurophysiology, and cognitive neuroscience. The principle has been translated by the artificial intelligence community into a body of algorithms used to train autonomous systems to operate independently in complex and uncertain environments, and constitutes the basis of cybernetics (Wiener, 1965; Sutton et al., 1998). Crucial to this paradigm is the concept of *reward*, which constitutes the driving force towards learning.

A typical scheme of reinforcement learning in engineering is presented in Figure 1.4.

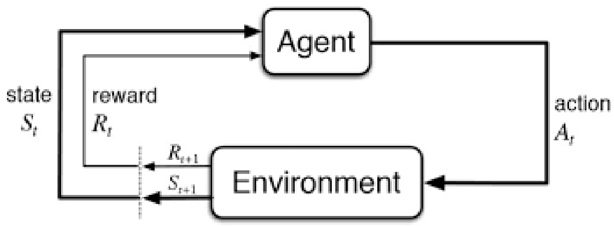

Figure 1.4: Agent-environment interaction in a reinforcement learning process.

A state is a concrete and immediate situation in which the agent finds itself.

From any given state S_t, an agent sends output in the form of actions A_t to the environment, and the environment returns the agent's new state S_{t+1} (which resulted from acting on the previous state) as well as rewards, if the action led to positive outcomes.

In the field of psychology, this concept dates back to the late 19th century as it represent the key for human learning (Silvetti and Verguts, 2012). It explains that actions that are successful for the organism, will be strengthened and therefore repeated by the organism, while actions leading to unpleasant consequences will be penalized and following actions avoided. The human learning process is strictly related to the mechanisms of reward conceived as fulfilling of a prediction by a self-generated model. According to this approach, humans will exhibit behavior so as to maximize the outcome reward (and consequently, to minimize "punishment"). This prediction-error principle has been formalized in the model by Rescorla et al. (1972), which combines the Pavlovian theory of associative learning (association between stimuli and responses) (Watson and Rayner, 1920) with the concept of reinforcement brought up by another founder of behaviourism, Skinner (1990).

It is with the work of Schultz et al. (1993), that the link between reinforcement learning and neuroscience was officially established and still provides insights for the study of learning and the nervous system. From a neurological point of view, reinforcement learning is associated with mechanisms of mesencephalic dopamine release. As one of the principal goals of the brain is to predict rewarding events, dopamine neurons signal upcoming rewards and activate (in case of positive outcome) or disinhibit (in case of error) the apical dendrites of motor neurons in the anterior cingulate cortex, which allows the anticipation of, and motivation to receive, desirable outcomes. In both cases, the anterior cingulate cortex uses these predictive error signals to select and reinforce the motor controller that is most successful at carrying out the task at hand (Holroyd and Coles, 2002).

Music is known to be a rich source of auditory reward and pleasure (Berridge and Kringelbach, 2008; Leman, 2016; Maes et al., 2016), but one may ask: how can music actually generate reward? The answer to this question lies in the fact that music is essentially a sequence of acoustical inputs organized through time. While listening to known music the brain generates predictions, mainly based on two sources of expectations: explicit knowledge of how a familiar piece of music will unfold, and implicit understanding of the rules of music, in general based on previous music-listening history. These two forms of expectations have distinct neural correlates and both are capable of producing reward. In the case of completely new music, fMRI studies by Salimpoor et al. (2013) have shown that implicit expectations alone can activate the same mesolimbic regions involved in forming and assessing predictions. Even for unknown music aesthetic rewards arise from the interaction between mesolimbic reward circuitry and cortical net-works involved in perceptual analysis and valuation. It can be concluded that music by itself, both known and unknown is able to produce reward by stimulating mesencephalic dopamine releases.

Through musical means, motoric learning can be realized by coupling a rewarding musical feedback to a desired movement behavior, or vice versa, by providing unpleasant musical feedback to undesired movement behavior. We believe this approach is a valuable alternative for the currently more common (cognitive) strategy of using auditory feedback as mere information carrier, of either performance characteristics or performance outcome, allowing people to monitor themselves and adapt their behavior in response to an explicit target behavior (i.e. goal-based approach). In this dissertation, we developed sonification strategies that employ two different sources of reward in music, namely one based on alignment of music tempo with movement patterns and one that relates to the psychoacoustic quality of the sound itself, in particular the minimization of noise or dissonance present in the music.

Previous studies have exploited synchronization and entrainment mechanisms as source of reward, based on principles of prediction and agency (Buhmann et al., 2017; Moens and Leman, 2015; Moens et al., 2014) by using the sensory-motor prediction emerging reward. Results have shown that reward generated by music-to-movement synchronization can be effectively used to unconsciously alter running cadence -2.5% to +2.0% of the initial reference cadence (Van Dyck et al., 2015; Moens, 2018). The rewarding effect of synchronization to music is known to have an empowering effect on the listener (Leman et al., 2017; Leman, 2016). In chapter 2 we analyzed the effect of music synchronization on runners' foot strike impact loading and hypothesized that alignment of footfall with music beats would generate a feeling of agency, resulting in empowerment, and in turn increase foot impact loading. In chapter 6 we looked at ways to improve cyclists' pedalling synchronization to music by actively adding extra music layers. Reward also in this case is generated by synchronization of the different music layers which leads to phase locking with the music beats.

Another reward-targeted strategy used in this work was based on alteration of the audio quality. Typically, people find dissonant music and noise unpleasant to listen to, and it may therefore be used as a negative reinforcer (Juslin and Västfjäll, 2008). Negative reinforcers have proven to be effective also when standard reward mechanisms of dopamine release are impaired. An experiment by Frank et al. (2004) has shown that negative reinforcers are effective at behavioral modification also in the case of Parkinson patients. Parkinson's disease (PD) is a neurological disorder, whose pathological basis consists of the degeneration of the dopaminergic neurons. Patients are impaired in learning from positive outcomes (reward), while performance is preserved for learning based on negative outcomes (punishment). In general, when the negative musical reinforcer is linked to an incorrect physical behavior the agent will automatically alter physical parameters to obtain a positive reward (minimization of the negative reinforcer). The advantage offered by the use of music in this process is that physical modifications can occur at a subconscious level thanks to the embodied characteristics of music.

1.3 Methods

1.3.1 General methodology

The development and validation of the proposed feedback systems was based on empirical testing. Participants from different sports disciplines were recruited to test the systems. Movements and movement alterations during trials, were continuously acquired by means of sensors and the kind of sensors varied according to the specific sports applications. Audio streams were provided through headphones or speakers in real-time with the aim to modify/improve physical parameters through music-based biofeedback. A general schematic of the proposed music-based biofeedback is shown in Figure 1.5.

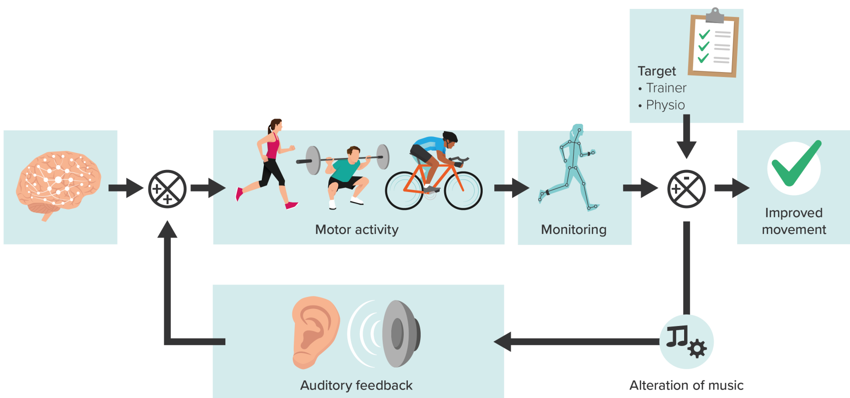

Figure 1.5: Illustration of the proposed biofeedback loop for sports movements modifications

The graph is based on a typical control theory backward feedback loop. Starting from the left, the mental voluntary process (represented by the brain) promotes the movement patterns for the specific physical activity (e.g. running, biking and weightlifting). The movement gets monitored and digitized through sensors (e.g. accelerometers, IMU systems, MOCAP cameras). The reconstructed movement is continuously compared to a target movement. The latter can be a standard value for injury minimization and rehabilitation or performance improvements, based on literature or suggestions by a trainer or physiotherapist. The difference between current and target movements represents the movement error and is converted into proportional alterations of a baseline music track. More specifically, in the experiments presented in the later chapters, music alterations consisted of, respectively: alterations of the audio quality of the music track or variation in the alignment between music beats and movement onsets. Perception of the auditory feedback signal sums up to the initial mental input of the movement and is responsible for movement modification.

Important in this paradigm is that the direction of the movement modification is not made explicit but it is up to the subjects to discover their own physical adaptation towards movement correctness. The process is stimulated by an embodied minimization of the music alterations which generates reward in the listener-agent.

1.3.2 Participants

All the reported experiments on subjects 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 prior to the experiments about the task at hand and signed a consent form in which they declared 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 only. The results of the tests were kept anonymous.

Recruitment of participants occurred via different channels. The most popular ones were: through the university participants database, through advertisement in gyms and sports facilities and through personal invitation by the experimenters. The difficulty of the tasks at hand was chosen so that participants could comfortably perform the complete tests. When working with independent groups, participants were distributed as equally as possible in terms of gender, age and level of expertise. Sports training status and musical background were also asked and used as covariates in the data analysis.

1.3.3 Stimuli

Selection of the audio stimuli is a crucial aspect while working with auditory feedback. Particular effort in the field of Auditory Displays is devoted to the choice of the specific audio to efficiently convey information through sounds (Hermann et al., 2011). An extended review of various kinds of sonification strategies in different applications is presented by Dubus and Bresin (2013). In the presented experiments, special time has been devoted to the choice of the music and the kind of the superimposed music alterations. The reasons behind the choice of the specific audio streams in the different applications are presented hereafter, for the music baseline and the alterations, respectively.

Music baseline Different music tracks were chosen for each specific application, in order to fulfil specific requirements. Music in general has the important characteristic to elicit pleasurable states in the listener.

In the cases in which the main focus was on synchronization of the music beats with the movement tempo (e.g. chapter 2 and chapter 6) a music piece was composed or selected to fulfil the following criteria:

Unknown: Motivated by the intention of excluding the effects of familiarity.

Instrumental: To avoid extra associations or effects and cultural impact caused by lyrics.

Clear beats: In order to optimize synchronization with the musical pulse.

In the experiment of chapter 3 and chapter 4, participants could choose their preferred music genre among pop, rock, dance, swing and world. The music pieces were pre-selected tracks with a relatively constant beat and with standard running cadence tempo, i.e. between $140 - 190$ Beats Per Minute (BPM). A playlist per genre was extracted from the larger database made available by Buhmann et al. (2017). Music tempo was continuously matched to the runner's Steps Per Minute (SPM) by time-stretching the music without pitch alterations. When the difference between SPM and music tempo exceeded a threshold value, a different track with closer BPM started playing.

In the experiment of chapter 5 a single instrumental music track specifically composed for the experiment was used. The goal of this track was to provide participant with a minimalistic and motivating beat during the exercise in order to focus on the music alterations (downsampling and panning) directly linked to the movement parameters.

Audio alterations In the case of audio-quality-based reward, music alterations were mostly a compromise between these two parameters: pleasantness and efficacy. Section 2 of chapter 3 carefully describes the experiments for the selection of music alterations among different types. Tests were performed between different coloured noises superimposed to the music, volume changes and sampling rate variations. Quantitative tests aimed at selecting the sonification with the best intensity level detectability and at deriving the empirical perception curve. Qualitative tests were also performed to determine/classify the clearest and most pleasant/least annoying among the alterations. Results of the tests showed that superposition of pink noise was the best performing type of music alteration in terms of level detection and pleasantness for most of the participants. This was chosen for the later tests of chapters 3 and 4.

In the synchronization-based reward strategy of chapter 2, music alterations consisted of different alignments of the music beat with runners' foot strikes. Music tempo was continuously stretched to achieve asynchronous states ($\pm 30\%$ of current SPM) or synchronous states (music tempo matched to runner's SPM or music beats continuously aligned with the footsteps) by using a modified version of the D-Jogger system (Moens et al., 2010). Alignment in this case is the source of reward causing empowerment. In the cycling experiments of chapter 6 music alterations consisted in the superposition of extra musical layers (beep, melody or drum sounds) on top a baseline melody.

1.3.4 Testing procedure

In this dissertation we describe several experiments to test the efficacy of our newly designed feedback systems. Inside the scientific method, an experiment is an empirical investigation in which a hypothesis is scientifically tested (McLeod, 2012). Within the experiment, an independent variable is manipulated and the dependent variable is measured; any extraneous variables are controlled. In our case the independent variables correspond to the music characteristics (audio quality or movement-to-music synchonization) and the dependent variable is the measured physical parameter of interest (i.e. foot strike impact loading, SPM, spine bending, barbell path and cycling cadence). The link between these variables is supported by the theory of embodied music cognition.

Most of the experiments took place in controlled environment, either laboratory settings or dedicated spaces. In this kind of experiment the researcher decides where the experiment will take place, at what time, with which participants, in what circumstances and using a standardized procedure. As indicated by McLeod (2012), the advantages of this kind of experiments are that these can be easily replicated and all external variables can be well controlled. The associated limitations are the low ecological validity and possible influence by the experimenters. No tests were performed to test the scalability of the systems to real-life settings and this would need to be done in a later stage.

Crucial to the proposed feedback strategies was the use of *real-time* and *continuous* feedback. These attributes of the feedback are only available thanks to the modern technological developments mentioned in section 1.1.2. Both quantitative and qualitative quantities were measured and analyzed in all experiments.

Quantitative data Quantitative measurements consisted of: motion data, music playback information and music alteration levels. The hardware systems for data acquisition were mostly developed inside the department and validated in comparison with commercial systems (see Van den Berghe et al., 2019). Most of these data were captured and logged using custom-built Max/MSP patches with implemented custom-built JAVA objects. Acquisitions took place at rates comprised in the range 100 to 1000 Hz. Recorded data corresponded to time-series of the parameters of interest. Average values of the time series were usually extracted from the time series in the time regions needed for the analysis. Reference measurements were carried out prior to the experimental trials and provided reference values for movement modifications. Most of the proposed feedbacks were tailored to the specific physical characteristics of the participant.

Qualitative data At the beginning of the experiment and after each trial participants were asked to fill in surveys about physical state and experience of the proposed feedback. Hereafter a list of our most used questionnaires:

General questions. Demographic information regarding the participants age, gender, education, music interest, etc.

Brunel Music Rating Inventory 2 (BMRI2) (Karageorghis et al., 2006). In order to have an idea about the motivational qualities of the music, participants 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"). Participants responded on a 7-point Likert scale anchored by 1 (strongly disagree) and 7 (strongly agree)

Physical Activity Enjoyment Scale (PACES) (Mullen et al., 2011). This is a questionnaire of 17 questions to be answered on a 7-point Likert scale. Respondents were asked to rate "how you feel at the moment about the physical activity you have been doing?". Higher PACES scores reflected greater levels of enjoyment.

Rating of Perceived Exertion Scale (RPE). Often referred to as the BORG scale (Borg, 1998), this scale ranges from 6 (no exertion at all) to 20 (maximal exertion), indicating how heavy the effort has been during the exercise.

Optional general comments about the system were usually asked at the end of the sessions.

1.3.5 Data 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 the analysis. In addition, assumptions of normality (Shapiro-Wilk 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 chosen for the statistical analysis of the data. In case the data were normally distributed, parametric tests, such as a t-test or (repeated measures) ANOVA were performed. In case of missing data for some of the conditions, mixed linear models were fitted and compared. 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. When analyzing nominal data from questionnaires Mann Whitney U tests were mostly employed. Either one of these tests resulted in accepting or rejecting the respective null-hypothesis. The p-value for significance was set to .05. In each study, the obtained p-values (significance) and effect sizes were reported.

1.4 Outline

The following chapters of the dissertation correspond to the different publications relative to the application of the developed feedback systems to different sports or with different purposes. The red line through them is the use of music and alteration of it, in terms of sound quality or movement-to-movement synchronization as feedback. The works are presented in chronological order from the beginning of the PhD.

In chapter 2 we investigated the effect of music synchronization on the foot strike impact loading for runners. In this case alterations of the music consisted in different alignments of the music beat with running foot strikes. This work also served as preliminary study for the use of synchronized or non-synchronized music in later studies dealing with foot strike impact reduction (see chapter 4).

Chapter 3 describes the development of music-based biofeedback and validations tests aiming at modifying runner's SPM, compared to standard verbal instructions.

In the work described in chapter 4 we exploited the same music alteration mechanisms of chapter 3 to reduce foot strike impact loading.

The goal of the biofeedback system in the experiments of chapter 5 was to improve weightlifting technique by creating awareness of the spine curvature and vertical barbell path. Also in this case a comparison was made between verbal feedback by a trainer and our music based biofeedback.

Different music alterations for cycling are reported in chapter 6. The goal of the experiment in this case was to investigate if adding movement sonification to a baseline music track could improve synchronization of the pedalling cadence to the music beat for application in the domain of training and rehabilitation.

The final chapter (chapter 7) 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.

Video material illustrating the experiments presented in the above chapters can be found at: www.valeriolorenzoni.com/rd/

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

2

The effect of (a)synchronous music on runners' lower leg impact loading

Valerio Lorenzoni, Tijl De Bie, Thierry Marchant, Edith van Dyck and Marc Leman

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Abstract

Running with musical accompaniment is becoming increasingly popular and several pieces of software have been developed that match the music tempo to the exerciser's running cadence, i.e. foot strikes per minute. Synchronizing music with running cadence has been shown to affect several aspects of the performance output and perception. The purpose of this study was to investigate the effect of synchronous music on runners' foot impact loading. This represents the ground reaction force on the runner's lower leg when the foot impacts the ground and is an important parameter for the prevention of tibial fracture injuries. Twenty-eight participants ran five times for three minutes and 30 seconds with a short break between each run. During the first 30 seconds of each running sequence, *participants ran at a self-paced tempo without musical accompaniment, and running speed and cadence were measured. Subsequently, they were requested to keep their reference speed constant for the following three minutes, with the help of three monitoring screens placed along the track. During this part of the experiment, the music was either absent (*No Music*), matched to the runner's cadence (*Tempo-entrained Sync*), phase-locked with the foot strikes (*Phase-locked Sync*), or played at a tempo 30% slower (*Minus 30%) *or faster (*Plus 30%) *than the initially measured running cadence. No significant differences between synchronous and asynchronous music were retrieved for impact loading. However, a non-negligible average increase of impact level could be observed for running sessions with music compared to running in silence. These findings might be especially relevant for treatment purposes, such as exercise prescription and gait retraining, and should be taken into account when designing musical (re-)training programs.*

2.1 Introduction

In recreational running settings, the use of music is remarkably popular and a wide range of music player software and devices is available, often tailored to the specific requirements of recreational and/or professional runners. This does not come as a surprise, as several authors have reported the positive effects of music in sports and physical activities. In particular, music was shown to distract from fatigue and discomfort (Bood et al., 2013; Fritz et al., 2013; Yamashita et al., 2006) enhance work output (Edworthy and Waring, 2006; Rendi et al., 2008), increase arousal (Szabo et al., 2009; Karageorghis and Priest, 2012; Karageorghis and Terry, 2011), and boost mood states (Edworthy and Waring, 2006; Shaulov and Lufi, 2009).

These motivational, psychophysical, and ergogenic effects can be associated with the empowering mechanisms deriving from musical interactions. Humans possess an innate expressive system that is responsible for encoding expressions into sonic cues (while playing), as well as decoding (while listening) and converting them into movements (Leman et al., 2017). Simply listening to music generates motor coordination-inducing schemes that respond to external sensory sources in such a way that they allow auditory-motor alignment and even the prediction of musical events (Maes et al., 2014). This prediction-fulfillment process represents a type of expressive alignment that generates reward (Salimpoor et al., 2015) and empowerment (Leman et al., 2017).

In this paper we focus on a specific expressive aspect of musical interaction, namely synchronization or, in this case, the adjustment of the musical tempo (and phase) to the running foot strikes. Previous research found that the above-described effects of music are further emphasized when synchronous music is used to accompany motor tasks (Karageorghis et al., 2009; Simpson and Karageorghis, 2006; Terry, Karageorghis, Mecozzi Saha, and D'Auria, 2012). Synchronization with the musical pulses or beats (conceived as basic musical elements, from which more complex structures emerge, see e.g. Burger, Thompson, Luck, Saarikallio, and Toiviainen, 2013) is a fundamental component of musical interaction, as it is a straightforward and spontaneous way to deal with the perceived stimulus. Leman (2016) refers to the use of movements for active control, imitation, and prediction of beat-related features in the music as *inductive resonance* . According to Morillon et al. (2015), the human motor system acts cooperatively with attention that is sharpened by the perception of periodic signals. Music is an example of a periodic stimulus (via pulse and beat) so it is not surprising that it is composed specifically for movement and dance (Wang, 2015).

Several studies have exploited synchronization and entrainment mechanisms as sources of reward, based on principles of prediction and agency (Buhmann, Moens, Lorenzoni, and Leman, 2017; Moens et al., 2014). Van Dyck et al. (2015) found that runners adapt their exercising cadence when spontaneously synchronizing to the musical stimulus. Leman et al. (2017) showed that being locked to the beat of the music produces a feeling of agency in the listener, as though they had taken control of generating the music, thus evoking a state of physical and mental stimulation experienced as *empowerment* .

Some have examined the use of synchronous versus asynchronous music in sports and exercise activities. Bacon, Myers, and Karageorghis (2012), for instance, studied the effects of synchronous and asynchronous music on oxygen uptake, heart rate (HR), perceived exertion, and motivation while cycling at submaximal intensities. Oxygen uptake levels were lower in the synchronous music condition than in the asynchronous music condition but there were no other significant results. Similar tests by Lim, Karageorghis, Romer, and Bishop (2014) focused on the effect of synchronization on oxygen uptake, HR, ratings of dyspnea and limb discomfort, affective valence, and arousal during cycling at fixed exercise intensities. Cyclists' performances were compared in the following conditions: with synchronous and asynchronous music, without music, and with a metronome. Synchronization had no effect on oxygen uptake but positive affective valence was higher in the two conditions with music than the conditions without music or with a metronome. Arousal was higher in the synchronous music condition than in the asynchronous music condition.

The effect of musical synchronicity was further investigated for treadmill walking and circuit-type exercises. In a treadmill experiment, results indicated that motivational synchronous music elicits ergogenic effects and enhances in-task affect during an exhaustive endurance task (Karageorghis, Mouzourides, Priest, Sasso, Morrish, and Walley, 2009). For circuit-type exercises, synchronous music was not shown to elicit significant ergogenic or psychological effects. However, there were differences between the sexes such that men showed more positive affective responses to the metronomic regulation of their movements than women (Karageorghis et al., 2010).

In an experiment on running performance by Bood et al. (2013), participants ran to exhaustion on a treadmill in a control condition without acoustic stimuli, a synchronized metronome condition, and a condition with synchronous motivational music matched to the assessed running cadence. Music with a prominent beat synchronized to the exerciser's pace was found to elicit the best performance as it helped to increase physiological effort and optimize running economy. Similarly, in experiments on 400-meter sprinting performances, Simpson and Karageorghis (2006) demonstrated that the qualities of the music promoting synchronization, but not its motivational qualities, are beneficial to recreational runners' anaerobic endurance performance. In a similar vein, Terry et al. (2012) showed that the motivational qualities of music were less important than the prominence of the musical beat and the degree to which triathletes are able to synchronize their movements to the tempo of the stimulus. They therefore suggest using synchronized, self-selected music during triathlon training programs. The improvements to performance reported in previous research are thus due mainly to the rhythmical structure of music rather than its motivational aspects. Those who engage in sports such as cycling, walking, and running benefit from synchronization, since coupling their movements to a constant musical beat enables them to work more efficiently.

The results of the studies outlined above indicate that music, especially synchronized music, has a significant ergogenic and psychophysical effect on sports and exercise performance, in particular on running and cycling. However, not much is known about the effect of music synchronization on biomechanical parameters. In the present study, the aim is to investigate the effect of synchronized music on runners' impact loading, i.e. lower leg loading when the foot strikes the ground. This represents an important biomechanical factor, which has not yet been studied with respect to music-to-movement synchronization, for two reasons: the severity of the impact loading is a known cause of runners' lower limb injuries, and it is directly linked to leg movement kinematics (van Gent et al., 2007). As such, influencing impact loading might have a direct effect on the health of the runner. Recent studies have focused on the reduction of impact loading through the use of real-time feedback. Using audio and visual feedback, Clansey, Hanlon, Wallace, Nevill, and Lake (2014) were able to reduce the impact of treadmill running performance. In this case, audio feedback was shown to be more beneficial than visual feedback. Moreover, Wood and Kipp (2014) stressed the efficacy of auditory feedback for reducing runners' peak tibial acceleration (PTA), an effect that was sustained in further retention tests.

Since a great deal of runners listen to music while exercising, we believe that an adequate understanding of the possible effects of synchronized music on impact loading is crucial in order to further optimize running technique and avoid injuries. In the present study, the effect of synchronized music on recreational runners' impact loading is scrutinized. As it has been shown that unintentional coordination is often manifested as relative or intermittent coordination (i.e. movements are attracted to a 0 or 180 but are not phase-locked, see e.g. Kelso, 1995; Lopresti-Goodman et al., 2008; von Holst, 1973), we tested both the effect of (1) synchronization based on entrainment of musical tempo and running cadence, without further coupling of the foot strikes and musical beats, and (2) synchronization incorporating phase-locking, thus matching foot strikes and beats. These conditions were further compared with a silent condition and two asynchronous conditions where music was either played 30% slower or faster than the exerciser's running cadence. We hypothesized that synchronization with the tempo of the music would generate a sense of empowerment in the exercisers (Leman, 2016) due to a stronger feeling of agency in music-to-movement alignment (Fritz et al., 2013), leading to an increase in foot strike vigour and consequently a higher impact loading.

2.2 Methods and materials

2.2.1 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.

2.2.2 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). With an level of .05 and a power of 95, based on an estimated low to moderate effect size, it was indicated that around 26 participants would be required.

Participants consisted of 28 non-professional runners (13 female and 15 male) of age comprised between 18 and 42 years (mean = 24.43, *SD*= 5.27). Of all the participants, 17 were formally trained in music; 13 were educated in a music academy, 2 were self-educated musicians, and 2 received private lessons. The majority of participants (27) went jogging at least once a month; 5 about once a month, 8 about once a week, and 14 several times a week.

2.2.3 Apparatus

The runners were equipped with two 3-axes digital accelerometers, attached in front of the tibial bone to the lower legs, to detect impact strength and cadence. The accelerometers were connected to a Teensy 3.2 micro-controller, in turn connected via USB to a 7" tablet (Panasonic Roughpad FZM1) mounted on a backpack carried by the runner. The step detection was performed in real-time using an in-house developed JAVA program, which ran on the tablet. The music player and music adaptation tools were implemented in Max/MSP from Cycling '74 (https://cycling74.com) and ran on the same tablet. The music was played through Sennheiser HD60 headphones. Speed measurements were performed in real time using a sonar system (MaxBotix, LV-MaxSonar-EZ: MB1010) connected to the tablet. The sonar detected marker rods of 1.90 m height, placed at regular intervals of 10.10 m next to the running track. Absolute speed was determined by computing the time intervals between the rods. The speed values, sent from the tablet, were displayed on three screens placed along the track at intervals of 107 m, to provide visual feedback to the runners regarding their speed. Specifically, the current speed value was displayed and the background screen color turned blue when the speed dropped more than 10% under the initial reference velocity (first 30 seconds). It turned red when the speed was more than 10% above the reference and green if within $\pm$ 10% of the reference, for each session independently.

2.2.4 Musical stimulus

The same musical stimulus was played throughout the entire experiment. The stimulus was composed specifically for this experiment by Myrthe van de Weetering[1] and fulfilled the following requirements (by analogy with Karageorghis, 2009; Van Dyck et al., 2013):

- *Unknown* : Motivated by the intention of ensuring optimal control over all musical parameters and to exclude effects of familiarity.
- *Instrumental* : To avoid extra associations or effects and cultural impact caused by lyrics.
- *Clear beats* : In order to optimize synchronization with the musical pulse.

2.2.5 Experimental procedure

The experiment was conducted on the outer track of the Flanders Sports Arena of Ghent, Belgium. At the start of the experiment, participants filled out a questionnaire on their personal background, music education, and sports training. Next, they were equipped with the accelerometers, backpack, and headphones. Each participant was asked to run five sessions on a 320 m running track, each session lasting for three minutes and 30 seconds. No information was provided concerning the real purpose of the experiment and all participants ran on their own. After each session, a break of approximately five minutes was introduced to enable the participants to recover sufficiently. During the break they were asked to fill out a Rating of Perceived Exertion (RPE) questionnaire and indicate how heavy the effort had been during the exercise, ranging from 6 (”no exertion at all”) to 20 (”maximal exertion”) (Borg, 1998). In addition, for the conditions with music, they rated the level of physical enjoyment of the run they had just completed on an 8-item version of the Physical Activity Enjoyment Scale (PACES) (Kendzierski and DeCarlo, 1991), using a 7-point Likert scale. In order to test the motivational properties of the musical alignment strategy they had used, participants also performed the Brunel Music Rating Inventory 2 (BMRI-2) test (Karageorghis, Priest, Terry, Chatzisarantis, and Lane, 2006).

A different condition was tested in each of the five running sessions. The conditions were presented in randomized order across participants. Running speed,

[1] www.myrthevandeweetering.com

cadence, and impact loading were measured in all sessions. The first 30 seconds of each session (‘assessment phase’) featured no music and were used to calculate the initial impact level and cadence, as well as the runner’s own comfort speed. Runners were asked to maintain the same speed in the following three minutes of each session (‘testing phase’), with the help of the three monitoring screens placed along the track. Speed could vary across conditions, as the experiment was designed to be ecologically valid as possible and minimize fatigue effects.

During the three minutes of the testing phase the following experimental conditions were imposed:

No Music was a control condition in which no music was played for the entire duration of the session.

Minus 30% and *Plus 30%* were both asynchronous conditions in which the music was played in a tempo differing by 30% from the assessed cadence. In *Minus 30%* , the tempo of the music (BPM) was adjusted continuously to a level 30% lower than the actual running cadence (SPM), while in *Plus 30%* , the same adaptation occurred but in a 30% faster tempo than the actual cadence. No auditory-motor synchronization could be achieved by the runner in either case.

In the *Tempo-entrained Sync* and *Phase-locked Sync*conditions, the musical stimulus was synchronized with the runner’s behavior. In the *Tempo-entrained Sync* condition, the tempo of the music was matched to their initial cadence, as measured in the assessment phase. In the *Phase-locked Sync* condition, a customized version of D-Jogger (Moens, van Noorden, and Leman, 2010) was used. Based on Kuramoto’s numerical synchronization model (Acebron et al., 2005), this enables the phase locking of each beat of the music with each of the runner’s foot strikes.

A time-stretching algorithm (Max/MSP elastic~ object) was used in the four music conditions to modify the tempo of the music without affecting its pitch. Table 2.1 provides an overview of the experimental conditions.

No Music	Reference condition: No music
Minus 30%	Asynchronous condition: Music tempo adaptively 30% lower than running cadence
Plus 30%	Asynchronous condition: Music tempo adaptively 30% higher than running cadence
Tempo-entrained Sync	Synchronous condition: Music tempo matched to initial running cadence
Phase-locked Sync	Synchronous condition: Musical beats locked to foot strikes

Table 2.1: Overview of the experimental conditions.

2.2.6 Data acquisition

For each condition, the peaks of the resultant tibial acceleration measured by the accelerometers were calculated using an in-house JAVA program. These are representative of the runner's lower leg impact loading. Hereafter, impact loading values are referred to as *impact level* and expressed in g. Cadence was also calculated (through a moving average over five steps) by the same program. The impact level and cadence were transmitted continuously as OSC messages to an in-house Max/MSP program running on the same tablet. The program implemented the synchronization strategies and provided the audio stimulus through the headphones. In addition, impact level and cadence were collected for every step detected and stored as .txt files on the tablet, together with the speed measurements by the sonar.

2.2.7 Data analysis

To avoid possible start-up effects, median values of the impact level, cadence, and speed were calculated, respectively, after 10 seconds from the start of the assessment phase and after 30 seconds from the start of the testing phase. The final 30 seconds of the testing phase were also excluded from the analysis as it is possible that participants altered their running behavior (e.g. slowing down or speeding up) in anticipation of the ending of the sequence.

To evaluate the effect of the different conditions on the impact level, *g-difference* (i.e. difference between median impact level of the testing and assessment phase) was computed for each participant and each condition. Due to minor technical issues during the acquisition, (mainly due to loosening of the accelerometers caused by sweat), the data collected in one of the experimental conditions for four of the participants were disregarded. In total, 136 observations were included in the analysis. A mixed linear model was applied with one independent variable (*g-difference*), two fixed effects (*speed* and *condition*) and one random effect (*participant id*). Speed in this case refers to the average speed throughout the whole condition, which was shown to be constant between assessment and testing phase, for all participants and conditions (see Table 2.2). Four versions of this model were considered, varying the set of predictors (but always including *participant id*): the null model (model 0, without *speed* and *condition*), the full model (model F, with *speed* and *condition*), and two intermediate models (model S with *speed* and model C with *condition*). The models were fitted by means of the R function 'lmer' (package lme4) and compared with each other using the R function 'ANOVA'.

2.3 Results

2.3.1 Preliminary analysis of speed

As previous research indicated that doubling running speed corresponds to an approximate 80% increase of impact loading (Breine, Malcolm, Frederick, and De Clercq, 2014; Mercer, Vance, Hreljac, and Hamill, 2002), participants were requested to keep a constant speed throughout each running sequence. This was facilitated by visual speed feedback on the three screens placed along the track.

To check if this constraint was met, *post hoc* statistical tests were performed on the difference between median speed in the *assessment* and testing phase for all participants and conditions. The differences for the *Minus 30%, Tempo-entrained Sync*, and *Phase-locked Sync* conditions were normally distributed over the participants (Shapiro-Wilk test, p= .758, .922, and .633), while differences for the *No Music* and *Plus 30%* conditions were non-normally distributed (p =0.006 and p = 0.001)

Paired t-tests were performed on the normally distributed pairs and Wilcoxon tests on the non-normally distributed ones. Comparisons showed no significant differences between the distributions in assessment phase and testing phase for any of the conditions. Results are shown in Table 2.2. Therefore, speed was assumed to be constant throughout the different phases in all conditions.

Condition	**Assessment phase**	**Testing phase**	**Test statistic**	***p***	***r***
No Music	11.06	10.81	z = 1.88	0.063	0.25
Minus 30%	11.05 (0.37)	11.01(0.37)	t = 0.34	0.731	0.07
Plus 30%	10.81	10.91	z= -1.43	0.104	-0.18
Tempo-entrained Sync	10.85 (0.32)	10.89 (0.33)	t = -0.52	0.606	-0.1
Phase-locked Sync	11.21 (0.34)	11.13 (0.36)	t = 0.57	0.576	0.12

Note. For t-tests, standard errors (M (SE)) and test statistics (t) are reported. For Wilcoxon tests, median (Mdn) and test statistics (z) are reported. For both tests, significance values (p) (significant main effect) and effect sizes (r) are reported*

Table 2.2: Mean speed [km/h] comparisons between the assessment and testing phase across conditions.

2.3.2 Differences between conditions

The effect of the different conditions on impact loading level was investigated using the four mixed linear models described above. Visual analysis of the normal Q-Q plots of the residuals for all the models revealed some deviations from normality. Therefore, 16 observations corresponding to extreme residuals in all four models were considered as outliers and deleted. The four models were then again fitted using the clean data set. Four Shapiro-Wilk tests for the residuals of the four models with the clean data revealed no deviation from normality (p = .082, .271, .157, .129 for model 0, C, S and F, respectively). The lowest Akaike Information Criterion (AIC) was obtained for model S (AICS = 354.00, AIC0 = 357.50, AICF = 357.80, AICC = 360.50). Besides, analysis of variance (ANOVA) showed that the amount of variance explained by model S was significantly higher than that explained by the null (0) model (p = .023, df = 3), while the same analysis for model S and the full model (model F) yielded p = .153 (df = 4). Comparison of model C (condition only) with the null model (0) yielded p = .296. It can therefore be concluded, that speed is a predictor of g-difference while we found no evidence that condition is a predictor. The estimated regression coefficient for speed was .20.

2.3.3 Pairwise differences

Comparisons were made between the distributions of impact levels in the assessment and testing phase, for each condition separately. Median values are presented in Figure 2.1.

Shapiro-Wilk tests revealed that impact level differences in the *Minus 30%* condition were normally distributed (p = .194) as were those in the *Plus 30%* condition (p = .132). Impact level differences in the *Tempo-entrained Sync* (p< .001), *Phase-locked Sync* (p < .001), and *No music* (p = .002) conditions were not normally distributed. Paired t -tests were used to compare the normally distributed pairs, Wilcoxon tests the non-normally distributed ones. A summary of the results is shown in Table 2.3.

Significant differences between median impact levels in the two phases were found in all conditions, except the *No Music* condition. Overall, in the music conditions, impact level was about 17% higher in the assessment phase than in the testing phase, on average.

A comparison of the g-difference (impact level in testing phase minus impact level in assessment phase) between people with and without music education was carried out using Mann-Whitney U tests. The two groups were not observed to differ significantly across conditions, as shown in Table 2.4.

Mean cadence was analyzed using the same mixed linear models as described before. Comparison of the null model (0) with model 1 (condition only) revealed

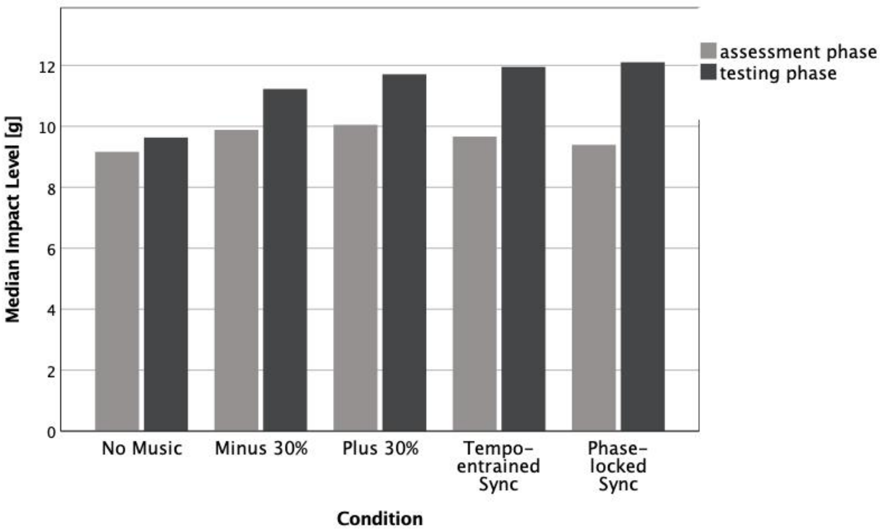

Figure 2.1: Median impact levels across all participants for the five conditions, respectively for the assessment and testing phase.

Condition	**Assessment phase**	**Testing phase**	**Test statistic**	***p***	***r***
No Music	9.16	9.63	z = -1.48	0.137	-0.2
Minus 30%	10.48 (0.87)	12.03 (0.93)	t = -4.17	< .001*	-0.63
Plus 30%	10.05 (0.88)	11.71 (0.99)	t = -3.78	.001*	-0.59
Tempo-entrained Sync	9.66	11.95	z = -3.73	< .001*	-0.49
Phase-locked Sync	9.39	12.1	z = -4.08	< .001*	-0.54

Note. For t-tests, standard errors (M (SE)) and test statistics (t) are reported. For Wilcoxon tests, median (Mdn) and test statistics (z) are reported. For both tests, significance values (p) (significant main effect) and effect sizes (r) are reported.*

Table 2.3: Impact level [g] comparisons between the assessment and testing phase across conditions.

Condition	**Musical training**	**No musical training**	*z*	***p***	***r***
No Music	-0.07	0.52	-1.22	0.237	-0.23
Minus 30%	1.07	0.78	0.65	0.537	0.12
Plus 30%	0.95	0.81	0.16	0.89	0.03
Tempo-entrained Sync	1.62	0.68	2.14	0.033	0.4
Phase-locked Sync	0.84	0.73	0.11	0.935	0.02

Note. Median g-differences (Mdn) are reported, as well as test statistics (z), significance values (p), and effect sizes (r).

Table 2.4: g-difference (testing phase - assessment phase) [g] comparisons between musically trained (n=17) and non-musically trained (n=11) participants.

a barely-significant difference (p = .051, df = 6). There was no significant difference between the null model and Model S (speed only) (p = .216). These results suggest that, in the present experiment, neither synchronization nor running speed significantly influenced running cadence. However, synchronization to music has the potential to affect running cadence (p = .051). Pairwise comparisons of median cadence distributions in each condition in the assessment and testing phase did not yield any significant differences, as shown in Table 2.5.

Condition	**Assessment phase**	**Testing phase**	**Test statistic**	***p***	***r***
No Music	163.83 (2.27)	163.50 (2.31)	t = 0.55	0.727	0.07
Minus 30%	163.67 (2.14)	163.33 (2.01)	t = 0.64	0.527	0.13
Plus 30%	164.02 (2.18)	163.13 (2.04)	t = 1.05	0.302	0.2
Tempo-entrained Sync	163.29 (2.15)	162.48 (2.77)	t = 0.56	0.58	0.11
Phase-locked Sync	164.51 (2.18)	164.98 (2.06)	t = -0.69	0.494	-0.13

Note. Median g-differences (Mdn) are reported, as well as test statistics (z), significance values (p), and effect sizes (r).

Table 2.5: Cadence [SPM] comparisons between the assessment and testing phase across conditions.

Questionnaire data Participants were asked to rate perceived exertion levels (RPE), level of enjoyment (PACES), and the motivational properties (BMRI-2) of the different synchronization strategies. Friedman tests yielded no overall significant difference across conditions (RPE:$\chi^2(4) = 1.95$; $p = .744$; PACES:$\chi^2(3) = 7.36$; $p = .113$; BMRI-2:$\chi^2(3) = 9.02$; $p = .081$).

Mann-Whitney U tests were used to compare the perceived exertion levels (RPE) of habitual runners (running multiple times per week) (n = 13) and non-habitual runners (running once a week or less) (n = 15). No significant differences between the two groups were found (see Table 2.6).

Condition	**Habitual runners**	**Non-habitual runners**	***z***	***p***	***r***
No Music	13	15	-0.65	0.525	-0.12
Minus 30%	13	15	-0.93	0.363	-0.17
Plus 30%	12	16	-0.63	0.555	-0.12
Tempo-entrained Sync	13	15	-0.72	0.496	-0.14
Phase-locked Sync	11	17	-1.83	0.072	-0.35

Note. Median levels of perceived exertion (Mdn) are reported, as well as test statistics (z), significance values (p), and effect sizes (r).

Table 2.6: Comparison of level of perceived exertion (RPE) (on a 6-20 Borg Scale) for habitual (n = 13) and non-habitual (n = 15) runners.

Significant differences between the ratings of enjoyment and motivational characteristics of musically (n = 17) and non-musically trained participants (n = 11) were observed for some of the experimental conditions (see Tables 2.7 and 2.8). The *Plus 30%* and *Phase-locked Sync* conditions were enjoyed more by musically than non-musically trained participants, and the *Phase-locked Sync* condition was perceived as more motivational by musically- than non-musically trained participants.

Condition	**Musical training**	**No musical training**	***z***	***p***	***r***
Minus 30%	5	4	-1.62	0.122	-0.31
Plus 30%	5	4	-2.24	.029*	-0.42
Tempo-entrained Sync	5	5	-1.62	0.134	-0.31
Phase-locked Sync	5	4	-2.6	.013*	-0.49

Note. Median levels of enjoyment ratings (Mdn) are reported, as well as test statistics (z), significance values (p), and effect sizes (r).

Table 2.7: Comparison of level of enjoyment ratings (PACES) (on a 7-point Likert scale) between musically trained (n=17) and non-musically trained (n=11) participants, across conditions.

Condition	**Musical training**	**No musical training**	***z***	***p***	***r***
Minus 30%	5	4	-1.21	0.251	-0.22
Plus 30%	5	4	-0.41	0.711	-0.08
Tempo-entrained Sync	5	5	-1.51	0.147	-0.28
Phase-locked Sync	5	3	-2.08	.043*	-0.39

Note. Median levels of perceived exertion (Mdn) are reported, as well as test statistics (z), significance values (p), and effect sizes (r).

Table 2.8: Comparison of music motivational characteristics ratings (BMRI-2) (on a 7-point Likert scale) between musically trained (n=17) and non-musically trained (n=11) participants across conditions.

2.4 Discussion

The aim of this study was to investigate the effect of auditory-motor synchronization on runners' impact loading. We hypothesized that this type of expressive interaction with music would generate an increased sense of empowerment and, consequently, increase the foot impact strength, resulting in an increased lower leg loading. This hypothesis was rejected by the present study, as no significant effect on impact loading could be ascribed to either tempo-entrained or phase-locked synchronization with the musical stimulus, nor to a non-synchronously played musical stimulus. Although previous research suggested that synchronized music might influence some characteristics of the performance output (e.g. Bood et al., 2013; Simpson and Karageorghis, 2006; Terry et al., 2012), our results suggest that impact loading is not one of the movement parameters that can be influenced by music aligned with running behavior.

Our results showed no significant differences between the motivational properties of, or enjoyment ratings for synchronous and asynchronous musical accompaniment. This is in line with the findings of research on sub-maximal intensity cycling performance, which yielded no differences in reported motivational qualities or affective valence ratings for similar stimuli (Bacon et al., 2012; Lim et al., 2014).

Most of the previous research dealing with auditory-motor coupling in sports and exercise performance has focused on tempo entrainment, or the alignment of the musical tempo with the exerciser's running cadence, without considering the relationship between foot strikes and musical beats. However, Leman (2016) indicated that this relationship should be taken into account when analyzing the psychophysical, motivational, and ergogenic effects on motor activities of synchronization, specifically, as this is directly related to embodiment and agency (Leman, 2016). In the present study, therefore, a condition in which musical beats and foot strikes were phase-locked, thus perfectly matched, was included as well as the tempo-entrained condition. As the findings of previous research have shown that not all people are inclined to synchronize to music spontaneously or even to do so when instructed (Buhmann, Desmet, Moens, Van Dyck, and Leman, 2016), synchronization was imposed externally by matching musical tempo/beats with running cadence/foot strikes.

Analysis of questionnaire data yielded no significant differences between the perceived exertion levels reported in the different conditions, or by habitual and non-habitual runners. Although musical training did not have a direct influence on impact loading levels, musically- and non-musically trained participants differed in terms of their enjoyment of and perception of the motivational qualities of the music: in particular, musically-trained participants found the *Phase-locked Sync* and the *Plus 30%* conditions more enjoyable than non-musically trained participants, and considered the music in the *Phase-locked Sync* condition more motivational. In this condition, the musical beats were constantly aligned with the runners' foot strikes, thus creating an even stronger connection between the movement behavior and the musical stimulus. This time-locking of internal and external pulses is believed to evoke a strong empowering effect, generating a feeling of agency in the listener as though they had taken control of generating the music (Leman et al., 2013; Moens et al., 2014). Similar agency is experienced when playing a musical instrument, potentially explaining why musically-trained participants enjoyed this experimental condition more than those who were not musically trained.

Interestingly, a non-negligible average difference in impact loading levels, but not speed or cadence, was found in running sequences without (assessment phase) and with music (testing phase). In all conditions with music, once it had started, an overall average increase of 17% was observed. This is one of the most striking findings of the present study, as it suggests that, irrespective of synchronization strategy, music has an empowering effect on the runner, resulting in an increased impact loading.

This effect on impact loading is possibly due to the attention shift mechanism as reported by Tenenbaum et al. (2004) and Karageorghis and Terry (2011). It might also be related to the often-reported arousal effect of music (Karageorghis and Priest, 2012; Karageorghis and Terry, 2011; Szabo, Balogh, Gar, Va, and Bo 2009) and the general finding that music distracts from fatigue and discomfort in exercise performance at sub-maximal intensities (Bood, Nijssen, Van Der Kamp, and Roerdink, 2013; Fritz et al., 2013; Yamashita, Iwai, Akimoto, Sugawara, and Kono, 2006), thus producing in augmented impact loading levels.

To our knowledge, the above-reported effect of music on this specific biomechanical parameter has not been unveiled before and would benefit from more specific and dedicated experimentation. Future research could possibly include other biomechanical parameters (e.g. vertical displacement and/or foot contact time) and could be more directly connected to injury prevention. Analysis of the kinematics of the process by use of cameras or multiple tracking sensors could shed more light on this phenomenon.

It would also be interesting to modify the relative durations of the phases with and without music, as fatigue effects might alter foot strike dynamics in a later phase of the session, leading to different lower leg loading levels, irrespective of musical onset (for a discussion of muscular fatigue effects on impact level, see Sheerin, Reid, and Besier, 2018).

No level of enjoyment (PACES) questionnaire was filled out for the *No Music* condition, since the physical activity to be rated in the PACES questionnaire was relative to running to music. This could be investigated in further experiments, although previous research clearly highlighted the higher level of enjoyment derived from music while exercising (Bood, Nijssen, Van Der Kamp, and Roerdink, 2013; Fritz et al., 2013).

It should be noted that, in the present case, the same musical stimulus (with clear and regular beats) was used in all conditions, which could have led to a general accentuation of movement properties due to the activating character of the music (Leman et al., 2013). Music with less pronounced beats might have affected the movement characteristics under study in a different manner. However, this stimulus was selected and maintained throughout the experiment to facilitate synchronization maximally and minimize possible confounding effects of, for instance, familiarity, preference, lyrics, or possible other (personal or musical) parameters. Further experiments could be dedicated to investigating the effect of the same synchronization strategies employing different musical stimuli. This subject was beyond the scope of the present paper; however, we are aware of the coupling of specific musical features and particular synchronization parameters.

In order to control for possible effects of fatigue, participants were entitled to select their own comfort speed at the start of each running session. In order to exclude it as a confounding variable, participants were asked to maintain the same speed throughout each experimental condition, and indeed no significant differences between speed measurements in the assessment and testing phases were found. Speed feedback was provided to the runner via the three screens placed along the track. These provided visual feedback by changing color if the speed in the testing phase changed more than 10% with respect to the assessment phase. This 10% range for feedback was selected to allow for some flexibility and to distract participants minimally. However, it could be argued that this range of variability might have been too extensive in terms of foot impact loading. The (almost significant) reduction in speed in the *No Music* condition (see Table 2.2) could partly explain the missing increase in impact level between assessment phase and testing phase for the No Music condition compared to the other experimental conditions (see Table 2.3). Smaller ranges for speed feedback in later experiments could reduce the influence of speed as a covariate when analyzing the effect of music-to-movement synchronization on impact loading.

Biomechanical studies by Mercer, Vance, Hreljac, and Hamill (2002) have revealed that an increase in running speed is directly coupled to an increase in impact loading. The analysis of the g-differences in the present experiment further revealed that average running speed is also a predictor of differences between impact loading before and after the start of the music with a positive regression coefficient (r = .20), implying that increasing speed causes an increase in impact level at the onset of the music. We ascribe this effect to the possibility that small variations in biomechanical parameters (foot-landing mechanism, knee angles, etc.) evoked by the onset of the music could lead to greater dynamical effects at higher running speeds than at lower speeds.

In order to make the experiment as ecologically valid as possible, we allowed speed to vary between conditions and participants. Although this enabled participants to exercise at their preferred pace, it increased the complexity of the analyses as speed was shown to be a covariate for differences in impact loading. This could be overcome in future experiments by imposing a standard comfort speed per participant.

Some technical problems occurred during the experiment, mainly because of the way the accelerometers were attached to the participants. Irregular oscillations of the sensors could result if the accelerometer became loose due to sweat. This occurred in a small number of cases but these data were excluded from the analysis.

To summarize, the findings of this study suggest that running to music significantly increases recreational runners' impact loading, irrespective of the specific alignment of the musical beats and foot strikes. This is especially relevant for treatment purposes, such as exercise prescription and gait retraining, and should be borne in mind when planning further research on impact reduction through acoustic feedback and when designing musical (re-)training programs. As far as we know, this aspect has not been investigated before and could be of particular relevance for high-impact runners. Further tests with fixed running speed and different music tracks would be required for strong conclusions to be drawn as to the effect of music on impact loading and other bio-mechanical factors. Nevertheless, the use of music in running training has been shown in a range of studies to increase arousal and improve performance, both of which are valid reasons to keep using music while exercising.

My main contribution is: development of the sonification system and experimental design, execution of experiment, main analysis of the data, and writing the page.

3

Design and validation of an auditory biofeedback system for modification of running parameters.

Valerio Lorenzoni, Pieter Van den Berghe, Pieter-Jan Maes, Tijl De Bie, Dirk De Clercq and Marc Leman

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Abstract

Real-time auditory feedback during sports activities is becoming increasingly popular in view of opportunities for monitoring and movement (re)training in ecological environments. However, the design of an effective feedback strategy is difficult. In this paper we present a methodical approach to the design of an auditory feedback strategy for running gait modification of recreational runners, using distortion of a musical baseline. First tests were conducted to select the best performing auditory distortion signal in terms of clarity and level perception, and to derive the relative perception curve. This was found to be pink noise with an exponential response curve. Further tests were carried out to determine the just noticeable difference of this signal in actual running conditions. Finally, validation tests were *performed to examine if the real-time auditory biofeedback, combined with music, could alter the runner's steps per minute (SPM) during treadmill-based running. The results show that our sonification strategy can alter the mean running SPM in a clear and non-disturbing way, and that our noise-based continuous feedback approach performs better than standard verbal instructions. Despite the fact that some of the participants did not respond effectively to the feedback, a large majority of the participants rated the feedback system as pleasant and indicated that they would use such system to improve their running style.*

3.1 Introduction

To regulate motor coordination and behavior, humans rely on different sensory feedback strategies (e.g. Scott, 2004; Winter, 2009). Sensory feedback can be naturally available through a person's sensing of the proper performance related to a task. This is called task-intrinsic feedback based on proprioception and exteroception. However, a person's performance can also be assisted by a coach (or a technological equivalent) who monitors the performance and provides feedback to the person. This assisted feedback can relate to the person's performance outcome (i.e., knowledge of the result) or to specific movement characteristics that lead to that outcome (i.e., knowledge of the performance) (Sharma et al., 2016). Obviously, such assisted feedback may be provided via different sensory modalities, typically through visual, auditory, or haptic feedback. Moreover, the feedback can draw upon conventional meanings (e.g. a red light to flag excess), or it can draw upon natural or inborn responses (e.g. the startle reflex in response to a gun shot). In the first case, when the signal is culturally defined, we call it a cognitive signal. In the latter case, when the signal is confounded with human biology, we call it an embodied signal (Leman, 2016).

Our goal is to design a sonification strategy for an assistive and embodied biofeedback system that impacts motor coordination. Overall, the term sonification is defined as "the use of non-speech audio to convey information" and "the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation" (Kramer et al., 2010). However, while sonification can be used to comprehend an abundance of data as an alternative to visual inspection of data, sonification also applies to interactive systems, in particular, assistive interactive systems that use sounds, or music, to guide, or interact with, a person's motor coordination and movement behavior (Degara et al., 2015). Overall, auditory feedback has some important advantages compared to visual feedback, especially in a context of real-time assistive feedback, although the efficiency of an assistive feedback strategy obviously also depends on the complexity of the task at hand (Sigrist et al., 2013). In particular, auditory feedback allows one to keep better focus on the task while attention to the feedback is less distracting (Repp and Penel, 2002; Hermann et al., 2011). In addition, auditory feedback also strongly increases the possibility of having a portable system that may be used in ecological settings (Wood and Kipp, 2014). Given these advantages, sonification has been proven to be particularly relevant in the context of sports and motor rehabilitation (e.g. Effenberg, 2005; Bevilacqua et al., 2016; Dubus and Bresin, 2013; Maes et al., 2016). A sonification strategy to correct running parameters was used by Eriksson and Bresin (2010) specifically focusing on vertical displacement of the center of mass during running. However, it is also known that the possibilities for mapping movement parameters to sounds are countless and that methodic approaches for designing sonification strategies are needed (Degara et al., 2015).

In what follows, we focus on an assistive and embodied feedback approach that works with music. A portable version of a sonification system, for example, was developed by Forsberg (2014) using alteration of a baseline music coupled to target running parameters values. Music is of particular interest for sonification because many humans are highly skilled in synchronizing temporal and spatial aspects of their movements to parameters in the sound and music. The periodic character of the music (implied in the expressive timing of pulses and beats) fits well with the ability of the human motor system to act in concert with attention sharpened by periodicity in signals (Morillon et al., 2015), as music is often designed to dance and move upon (Wang, 2015). On top of that, a major asset of using music as feedback source concerns its ability to motivate and provide pleasure (Salimpoor et al., 2015). This feature may be related to its rhythmicity (Wang, 2015), which is valuable in contexts that often involve strenuous physical activity, boredom, and fatigue (Fritz et al., 2013). While previous studies have exploited synchronization and entrainment mechanisms as source of reward, based on principles of prediction and agency (Leman et al., 2017; Buhmann et al., 2017; Fritz et al., 2013; Maes et al., 2015; Moens and Leman, 2015; Moens et al., 2014; Van Dyck et al., 2015), we believe that other types of mechanisms can be exploited as well, and perhaps even in combination. Music is a highly embodied phenomenon in the sense that music listening goes together with motor activity. This provides a basis for enacting music, that is, for responding to music in such a way that movement responses seem to act the music (Leman et al., 2016). This ability draws upon predictive schemes that allow motor coordination to respond to external sensory sources in ways that allow motor-to-music alignment and even prediction of events in the sensory sources, with consequences for the emotional engagement. While the sonification strategy aims at allowing people to monitor themselves and adapt their behavior in response to an explicit target behavior (i.e., goal-based approach), we believe that the "embodied" approach, given its confounds with the human biology of reward-based behavior, may lead to successful strategies that outperform cognitive approaches to human empowerment (Leman et al., 2016).

At present our goal is to explore a mechanism based on a reinforcement learning paradigm (Maes et al., 2016; Silvetti and Verguts, 2012). This paradigm states that humans will exhibit behavior so as to maximize the outcome reward (and consequently, to minimize "punishment"). Through musical means, this can be realized by providing natural and rewarding escape solutions to unpleasant musical feedback. This approach could be called "embodied" in the sense that it is based on a direct behavioural change in response to punishment and reward. In contrast, a purely cognitive approach would not imply the reward system, as it would be based on a reasoning about the relationship between auditory feedback and movement coordination, such as a signal to indicate that movement should change in a particular direction. The latter could be a command by a coach, telling that the person's movement should go faster. The motivation and reward based approach is a valuable alternative for the currently more common cognitive approaches that use auditory feedback as messenger of conventional or learned meanings related to performance characteristics or performance outcomes (Leake and Ram, 1995).

In the present study, we hypothesize that (i) human beings are sensitive to auditory information in their environment, even when no instruction is given to attend to that auditory information, (ii) behavioral responses to auditory information are possibly regulated at an embodied level, disregarding cognitive involvement, (iii) auditory information can be confounded with biological mechanisms of reward processing.

To test our signification hypothesis, we developed a specific strategy based on the idea that music and its psychoacoustic quality can impact the human motivation and reward system. Psychoacoustic quality can be defined in terms of the degree of noise added to music so that the music becomes unpleasant (Juslin and Västfjäll, 2008). Accordingly, we use a reinforcement learning paradigm to induce motor coordination changes. In this paradigm, the noise added to the music acts as a negative reinforcer, which people can reduce by behavioral adaptation, in particular by a change in motor coordination. When this adaptation is regulated in a structural way, it may provide a basis for the development of a new motor coordination habit because reduction of added noise (due to adapted motor coordination) implies that music becomes more pleasant to listen to, which acts as a positive reinforcer to the new motor coordination habit.

In the present study we will validate our sonification hypothesis on recreational running, in particular on the ability to manipulate the runners' step rate (both increasing and decreasing). Step rate (SR), also known as running cadence and commonly expressed as steps per minute (SPM), is a temporal characteristic of the running gait with relevant implications in running economy and injury prevention. In particular, an increase in step rate during running was shown to reduce patellofemoral pain (Lenhart et al., 2014) and lower extremities loading forces (Willy et al., 2016; Luedke et al., 2016). Specifically, an increase of 17% in step rate was found to minimize vertical peak and loading rates on the lower extremities (Hobara et al., 2012). These measures of external loading have been associated with stress fracture susceptibility in a running population (van der Worp et al., 2016). Thus, modulating running SPM may be practical for minimizing the risk of developing tibial stress fractures due to reduced lower extremity loading.

The paper is organized as follows. Section 3.2 describes the design process of the feedback signals. Section 3.3 is entirely dedicated to the validation of the feedback system in a treadmill experiment, using the selected feedback. Finally, a general discussion is presented in Section 5.4.

3.2 Sonification design

3.2.1 Selection of the feedback signals and determination of the loudness response curve

The first step in the design of the auditory feedback was the selection of the feedback signals. Five different feedback signals were used:

- three noise signals separately superimposed on the music: *white noise*, *pink noise* and *amplitude modulated noise* (the last one being white noise amplitude-modulated to the music envelope).
- one *downsampling* (i.e. distortion of the music itself by reduction of the sampling rate by a factor from 1 to 100).
- one *volume reduction* (i.e. music volume decrease from 100% to 0%.

The goal was to select a feedback signal by means of a perceptual estimation task.

Procedure

Ten participants (age 34 $\pm$ 14 years, 4 females) performed a noise perception test. Participants took place in front of a computer and were equipped with Sennheiser HD60 headphones. The test was implemented in a specifically designed Max/MSP patch.

Noise and music signals were normalized to the same intensity, i.e. same root mean square (*rms*) value, after convolution with an equal-loudness Fletcher-Munson curve (Fletcher and Munson, 1933).

For each noise feedback signal, the participant listened to the noise signal level at an intensity level of 100% (of the music *rms*) superimposed on the music, during 5 seconds. For the downsampling signal, the participant had to listen to the 100 times downsampled music, during 5 seconds. For the volume reduction signal, the 100% level meant no audible signal during 5 seconds. Then, by pressing the space bar, a new feedback signal level between 0% to 100% was provided. In the case of a noise feedback signal, this was always in superposition with a music track whose intensity level was fixed. The task of the participant was to indicate the perceived intensity level of the feedback signal on a scale from 0 to 100, using the computer mouse.

This procedure was repeated for 10 different intensity levels of the feedback signal to span the range from 0% to 100%, presented in randomized order. Each level was provided twice during the session. The same procedure was repeated for all the feedback signals in randomized order. The whole process was repeated for two different music tracks, also in randomized order, for all the participants:

track 1: *Happy* by Farrel 2013

track 2: *Wildcat* by Ratatat 2006

The first track was chosen because it is a popular song and played with standard musical instruments. The second track is less known and has a more electronic sonority.

At the end of the tests participants needed to fill in a questionnaire about clarity and pleasantness of the different feedback signals. They were asked to specify which of the 5 proposed feedback signals they found to be: most clear/ least clear, most pleasant/least pleasant, most annoying/least annoying.

Results

Responses of all participants for each of the feedback signals were combined and interpolated using different fitting curves: linear, second order and exponential as shown in Figure 3.1.

A "good" sonification can be defined in terms of the accuracy of the mapping from *imposed* intensity level to *perceived* intensity level across the full range, from 0 to 100. If the accuracy is high, then we assume that the imposed noise levels can be effectively used to provide feedback to the runner. The fitting for each auditory input was thus evaluated by means of the average variance of the data around the inverse of the interpolation function, where the average is taken over the perceived range. This quantity can be expressed by the following integral:

$$I = \int_0^{100} \sigma(y)^2 f^{-1}(y) dy \tag{3.1}$$

Here $f^{-1}(y)$ indicates the inverse of the interpolation function and $\sigma(y)$ the estimated standard deviation. Note that this criterion penalizes scattering at the higher levels, where variations in perceived levels as a function of changes in imposed levels turn out to be higher (the non-linear interpolation functions have a steeper slope for higher imposed signal levels, see Figure 3.1).

Overall, pink noise with an exponential fit generated the smallest quantity I, from the integral of equation 3.1 (see Table 3.1). Accordingly, pink noise with exponential mapping was chosen for further experiments.

The same testing procedure was repeated for the two music tracks mentioned above, to check the influence of the music track on the perception curve. Figure 3.2 shows interpolation of *pink noise* data for the two tracks separately and the combined data. The difference between the distributions for the two tracks was found to be statistically non-significant (Wilcoxon test: W = 55, p = 0.7394). Consequently, the data for the two tracks have been combined and the resultant interpolation curve has been used in our sonification study. The fact that the difference

I	2nd order	exponential
White noise	1117.1	1089.9
Pink noise	985.1	954.3
AM noise	1542.7	1329.8
Downsampling	1478.1	1335.4
Volume decrease	1884.3	1715.4

Table 3.1: Values of the integral I for 2nd order and exponential fitting for all 5 feedback signals.

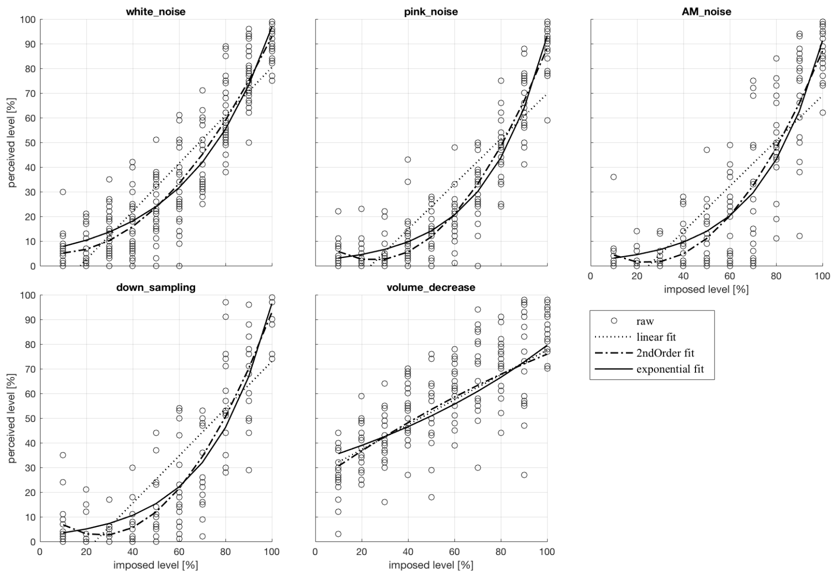


*Figure 3.1: Perception of the feedback signals' intensity. The horizontal axis indicates the imposed intensity level and the vertical axis the perceived intensity level. Intensity level is given in percentage of the music root mean square (*rms*) The feedback signals are: white noise, pink noise, amplitude modulated (AM) noise, down sampling and volume decrease. The lines show different fitting curves: linear fit (dotted line), 2nd order fit (dot-striped line) and exponential fit (full line).*

between the reference music tracks is small, justifies the use of different music tracks in combination with the designed feedback signals in the later experiments described in Section 3.3

Based on an analysis of the questionnaires, white noise was found to perform the best in terms of clarity by some of the participants (5/10 - most clear), but it was perceived as most annoying by some (4/10 - most annoying). Volume decrease was also perceived as most pleasant by some (6/10 - most pleasant) but not clear enough in regards to intensity level discrimination, as substantiated by the high

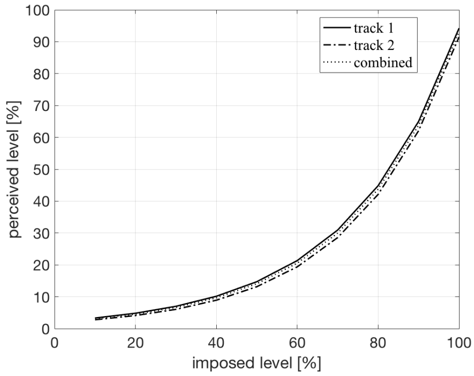


*Figure 3.2: Pink noise with exponential fitting curve for two different music tracks (solid line and dash-dotted line) and combined data fit (dotted line). The horizontal axis indicates the imposed intensity level and the vertical axis the perceived intensity level. Intensity level is given in percentage of the music root mean square (*rms*)*

scattering in the plots of Figure 3.1. Overall, pink noise scored relatively well in terms of clarity (3/10 - most clear) and pleasantness (4/10 - most pleasant) and this further motivated our choice to use pink noise for sonification.

3.2.2 Perception tests during running

Further tests were performed in order to tune the sonification parameters obtained from Section 3.2.1 in actual running conditions. Specifically, the quantity of interest was the just noticeable difference (JND) between intensity levels of pink noise. The latter is an important parameter for the design of auditory feedback systems (see Hermann et al., 2011). In what follows, we tested this in actual running conditions.

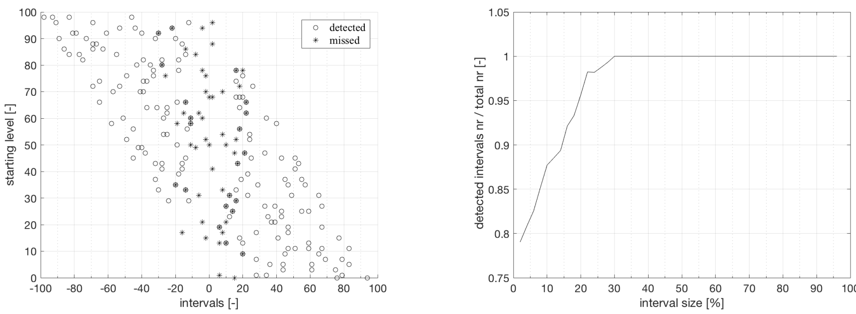
Procedure

Eleven participants (age 28 $\pm$ 4 years, 3 females) were asked to perform one run of 9 $\pm$ 0.5 min with music and superimposed randomized pink noise intensity levels. The experiment took place at the Sport Science Laboratory Jacques Rogge (Ghent, Belgium) on a 32 m long oval running track. Runners carried a backpack with a 7" tablet (Panasonic Roughpad FZ-M1) mounted on it. The weight of the backpack was 1.6 kg and it was properly attached to the back so that it was not felt as disturbing the natural running movement. The sonification was realized by a specifically designed Max/MSP patch and played by the same tablet through Sennheiser HD60 headphones. In this test the track *Happy* by Farrel 2013 was looped.

During the running trial, pink noise was added to the music at randomized intensity levels ranging from 0% to 100% of the music *rms* (see description in Section 3.2.1). A local area network was created by a TPLink router, also placed on the backpack. A remote computer was used to start and stop the experiment and to send the pink noise intensity values to the tablet. Runners were asked to rise their hand if they heard a change in noise intensity level. The responses were digitally recorded by the operator on the remote computer by visual observation with a spacebar click. The time at which the different pink noise intensity levels were provided was also randomized, to minimize habituation and false positives.

Results

The starting pink noise intensity level and the corresponding interval to the next intensity level were compared across all participants. Thereby, the minimum perceived intensity interval (i.e. the just noticeable intensity difference) was calculated as the boundary between detected and non-detected (missed) noise intervals.



(a) Scatter plot of intervals detection for all participants: detected (circles) and missed (asterirks)

(b) Ratio of the detected intervals number over the total number of intervals for increasing interval size

Figure 3.3: Results of noise intervals perception tests in running conditions.

The pink noise intervals are presented in Figure 3.3(a), with respect to the initial noise intensity level. If the starting noise intensity level is 0, then the noise intervals can only be positive. If the starting noise intensity level is 100, then the noise intervals can only be negative. The boundary between detected and missed intensity level intervals of pink noise lies somewhere between 20% and 30% for both positive and negative intensity level intervals. Furthermore, this boundary seems to be relatively constant for different starting levels (vertical axis).

Figure 3.3(b) displays the ratio of the number of detected intervals over the total number of intervals (detected and missed) for increasing pink noise intensity level interval size. For an interval size of 20% the detection probability corresponds to 95.6%. Therefore, an interval size of 20% has been chosen for further experiments, as this provides a reasonable high probability of the detection of a difference in pink noise intensity level. This finding then allows for the discretisation of the perceived noise range into a limited number of pink noise intensity levels, namely 5. User feedback in the experiments of Section 3.3 confirmed the high detectability of the chosen interval.

3.3 System validation

To test the efficacy of the proposed acoustic feedback on running gait parameters, an experiment was set up that aimed at modifying the step rate (hereafter referred to as SPM) during a treadmill running experiment.

3.3.1 Participants

Thirteen physically healthy participants with a physical education background (age 23 ± 3 years, 4 females) volunteered. Written informed consent was given before participation. Ethical approval was obtained from the local ethical committee (2015/0864).

3.3.2 Apparatus

The runners were equipped with two 3-axes digital accelerometers, one for each leg, attached to the lower leg in front of the tibial bone. These were LIS331HH accelerometers with digital output supporting a range of -24g to 24g and a sampling range of 1000Hz. Prior to the attachment of the sensor, the skin on the lower leg was pre-stretched with non-elastic tape to minimize oscillations due to inertia of the sensor. The accelerometers were connected to a Teensy 3.2 micro-controller and passed via USB to a 7" tablet (Panasonic Roughpad FZ-M1) mounted on a backpack, carried by the runners, as described in Section 3.2.2. Step detection and SPM calculation were performed in real-time using an in-house JAVA software running on the tablet. The music player and sonification strategy were implemented in a specifically designed Max/MSP patch and played by the same tablet through Sennheiser HD-25ii headphones. The audio output from the tablet was split into two output channels. The test leader was provided with headphones connected to the second output channel to monitor the audio signal sent to the participant. Experiments were performed on an instrumented treadmill (Bertec Corp, Worthington, Ohio, USA) at the Sport Science Laboratory Jacques Rogge (Ghent, Belgium). The passive noise cancelling feature of the headphone counteracted secondary noise of the motorized treadmill. A visualization of the set-up is provided in Figure 3.4.

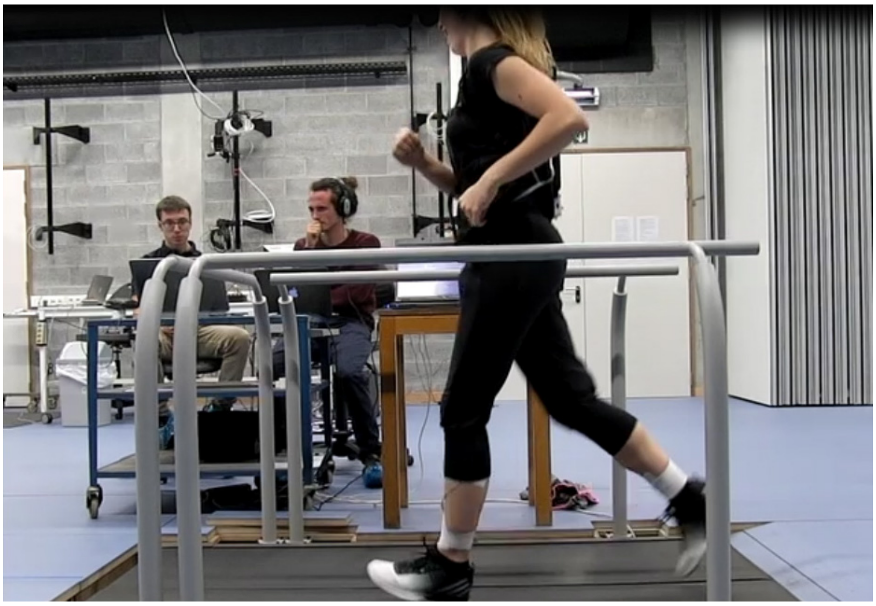


Figure 3.4: Experimental set-up for treadmill experiment.

3.3.3 Procedure and design

Each participant ran 4 experimental conditions in the same sequential order, at preferred speed between 9 ± 1 km/h. The conditions are described hereafter:

baseline The baseline condition consisted of a 3 min warm-up. The average SPM was determined by averaging from 1.5 min after the start over a time period of 1 min.

verbal instruction Participants were asked to run for 6 min at 15% higher SPM compared to their original SPM (from baseline), this time with music. An increase of +15% in SPM was chosen following the evidence provided in Hobara et al. (2012). The target tempo was indicated with metronome ticks, starting at 10 seconds prior to and ending at the start of the trial. This resembles a typical verbal instruction by a trainer during a training session, with no continuous feedback. Immediately following the 6 min run a first questionnaire was given to the participants with the request to rate their perceived exertion on a Borg scale (Borg, 1998) and to estimate the motivational aspects of the audio on an adapted BMRI questionnaire (Karageorghis et al., 2006).

noise feedback - fixed target Participants were informed that noise would have been added to the music and that this noise was coupled to their SPM. The five noise levels on top of a reference music track, were played to the participant prior to the trial. Participants were asked to try to improve the sound quality, but no noise reduction strategy was provided. The target in this case, was fixed to an increase of 15% of the baseline SPM for the whole duration of the trial. Noise feedback started 20 seconds after the start of the trial (10 seconds after the start of the music). At the end of the trial a second questionnaire similar to the first one was completed; in this case it also included ratings of the noise perception and perceived respondence of the system.

noise feedback - changing target The performance target SPM in this case, varied from +15 % of baseline SPM for the first 2 min, to -15 % of baseline SPM between min 2 and 4 and again to baseline SPM for the last 2 min. Instructions for this condition were analogous to the previous one. Subjects were asked to keep adjusting their SPM to minimize the noise. Also in this case, noise feedback started 20 seconds after the start of the trial (10 seconds after the start of the music).

A sketch of the last two experimental conditions (*noise feedback - fixed target* and *noise feedback - changing target*) is provided in Figure 3.5

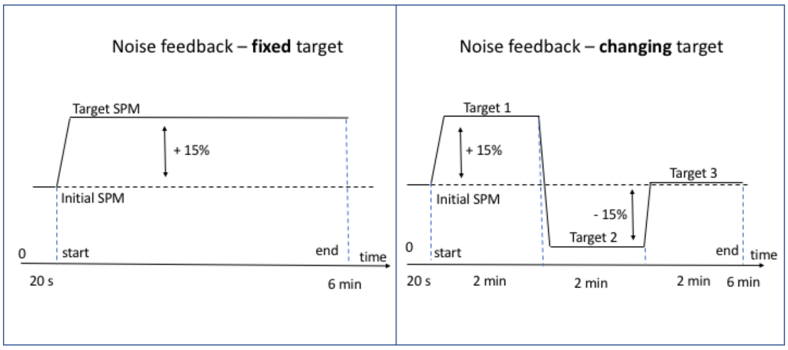


Figure 3.5: Sketch of the experimental conditions: noise feedback fixed target and noise feedback changing target

3.3.4 Acoustic stimuli

Music Participants could choose their preferred music genre among pop, rock, dance, swing and world. The music pieces were pre-selected tracks with a relatively constant beat and with standard running cadence tempo (between $140-190$ BPM). A playlist per genre was extracted from the larger database made available by Buhmann et al. (2017). Music tempo was continuously adapted to the runner's

prt1	prt2	prt3	prt4	prt5	prt6	prt7	prt8	prt9	prt10	prt11	prt12	prt13
164.6	156.8	149.6	156.8	161.4	170.4	160.2	165.4	145	167.2	170.8	157.8	165

Table 3.2: Initial average SPM values for all participants from experimental condition: baseline

SPM using the Max/MSP *elastic* time stretcher. When the difference between SPM and music tempo exceeded 4% for more than 8 s, a different track with closer BPM started playing. The time stretch threshold was an empirical value of noticeability determined during pilot tests preceding the experiment. No information was given to the runner regarding the synchronisation of the music.

Noise mapping For the *noise feedback - fixed target* condition the participant's current SPM was continuously mapped from 95% – 115% of the initial SPM onto the range 100 – 0. The resulting value was fed into the exponential response curve obtained in Section 3.2.1 and discretized in 20% intervals, according to the findings of Section 3.2.2. The resulting value corresponded to the intensity level of pink noise superimposed on the music. Level 0 indicates no noise, while level 100% means the same intensity level as the music *rms*. Analogous noise mappings were used in the *noise feedback - changing target* condition, but with different SPM mapping ranges (95% – 115%, 120% – 85%, 80% – 100%. All percentages are relative to the participant's baseline SPM.

3.3.5 Data analysis

To check the effectiveness of the sonification strategy compared to standard verbal instructions, a comparison was made between the *verbal instruction* condition and the *noise feedback - fixed target* condition.

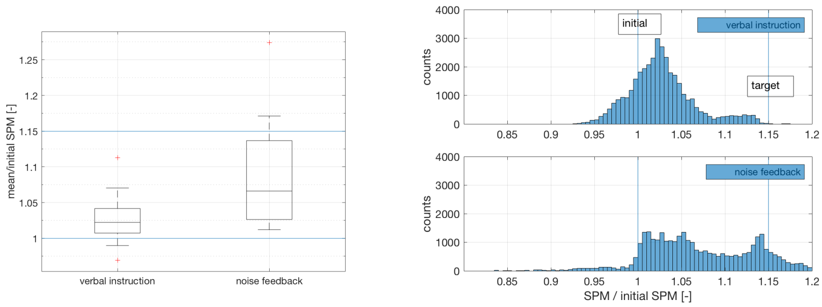
The mean values of the SPM were calculated for each participant and condition separately and normalized to the participant initial SPM as measured in condition *baseline*. The first and last minutes of the data acquisition were disregarded in order to avoid transients. Due to the relatively low number of participants and the non-normality of the distribution of the SPM data (Shapiro-Wilk test, p = 0.06), non-parametric statistical tests were performed.

A Wilcoxon signed-rank test was performed on the ratio of the mean SPM over the initial SPM (mean/initial SPM) as dependent variable and the experimental condition as within-subjects factor. The same test was also performed on the standard deviation of the SPM for the same two conditions: *verbal instruction* and *noise feedback - fixed target*.

The initial SPM for all participants evaluated in condition *baseline*, are reported in Table 3.2.

3.3.6 Results

Overall, the verbal instruction increases the SPM less than the noise feedback. The Wilcoxon test showed that there is a significant difference in mean/initial SPM ratio across the two conditions *verbal instruction* and *noise feedback - fixed target* ($p = 0.0046$). In particular for the *verbal instruction* condition Mdn = 1.0229, 95% CI [1.00590 1.04695], while for *noise feedback - fixed target* Mdn = 1.0662, 95% CI [1.0321 1.1394]. These results are visualized in the box plot of Figure 3.6(a). The horizontal lines from bottom to top represent, respectively, the initial SPM ratio (ratio = 1) and the target SPM ratio (ratio = 1.15).



(a) Mean/initial SPM ratio across conditions. The horizontal full lines at 1 and 1.15 represent, respectively, the initial SPM ratio and target SPM ratio

(b) Combined SPM distributions normalized with respect to initial SPM for all participants: *verbal instruction* condition (top) and *noise feedback - fixed target* condition (bottom). The vertical full lines at 1 and 1.15 represent, respectively, the initial SPM ratio and target SPM ratio

Figure 3.6: Ratio mean/initial SPM and normalized SPM distribution for all participants across conditions: verbal instruction *and* noise feedback - fixed target

Figure 3.6(b) shows the histograms of the combined SPM time series of all participants normalized to the corresponding initial SPM. The top plot refers to the *verbal instruction* condition while the bottom one to the *noise feedback - fixed target* condition. The vertical lines represent, from left to right, respectively the initial SPM (ratio = 1) and the target SPM (ratio = 1.15). Results show that the ratio distribution for the verbal input condition is relatively uniform around 1.02, meaning that participants in general increase SPM following the verbal instruction by a percentage of approximately +2% but remain quite far from the +15% target. In the case of noise feedback (Figure 3.6(b) bottom) the distribution of the normalized SPM is more spread and two separated areas can be distinguished: one near the target 1.15 ratio and another one ranging from 1.01 to about 1.06.

The standard deviation of the SPM for each subject was used to check differences in SPM stability across conditions, using a Wilcoxon signed-rank test.

The latter revealed that there is a relevant statistical difference across the two conditions (p = 0.0024) and that the scattering is considerably higher for the *noise feedback - fixed target* case Mdn = 2.297, 95% CI [1.12000 3.37785], compared to the *verbal instruction* condition Mdn = 0.977, 95% CI [0.83615 1.29255]. This could be explained by the fact that in the *noise feedback - fixed target* condition participants are experimenting with the system to get acquainted with it and that the higher achieved SPM is physically harder to keep up with.

Figure 3.7 shows the time series of all participants for the *verbal instruction* condition and the *noise feedback - fixed target* condition, as well as the initial SPM and target SPM lines. Time series of the condition *noise feedback - changing target* are presented in Figure 3.8. Participant 9 is not shown for this condition because of a technical problem during the last phase of the acquisition. This participant has been excluded from the analysis of this experimental condition.

3.3.7 Discussion

The results show an overall effectiveness of the proposed acoustic feedback compared to verbal instructions, although different responses were found across participants. The different behavioural responses among participants can be observed in Figure 3.7. For participants 1 and 2, the increase of SPM starts several seconds after the start of the condition, meaning that it required some time for them to grasp the auditory feedback strategy. Surprisingly, for participants 4 and 9, the verbal instruction strategy seems to work better than the noise feedback strategy. In contrast, participants 5 and 7 over-reacted to the sonification feedback by running at an average SPM higher than the target SPM. The authors ascribe this to a shift in kinematic pattern (as observed during the trials) in order to be able to minimize the noise in an uncomfortable SPM range.

Based on the above results it is possible to classify the participants in: task responders and task non-responders. A target value 7.5% SPM increase with respect to initial SPM was used in previous experiments with visual cues by Willy et al. (2016). Based on this criterion, we stipulated that if the mean SPM of the participant was above 50% of the target (SPM increase higher than 7.5% of the initial SPM) then the participant was classified as responder. In our study, participants 5, 7, 10, 11, 12, 13 were considered to be task responders, while participants 1, 2, 3, 4, 6, 8, 9 were considered task non-responders.

When the same 7.5 % criterion is adopted for classification of responders in the *noise feedback - changing target* condition, then the number of task responders decreases to 4 (participant 5, 11, 12 and 13). Non surprisingly, the responders of the *noise feedback - changing target* condition are also responders of the *noise feedback - fixed target* condition. The reverse is not true and this effect can be ascribed to the required motor skills needed in the changing target condition. Interestingly,

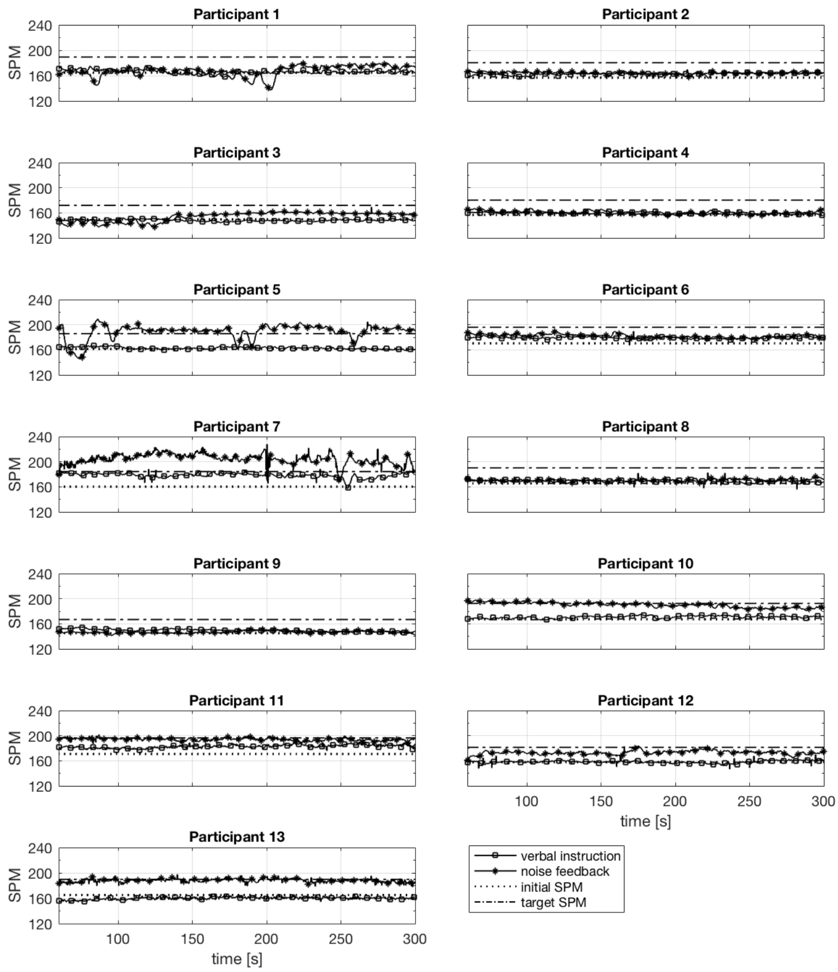


Figure 3.7: SPM time series in conditions: verbal input *(square-marked line) and* noise feedback - fixed target *(diamond-marked line) for all 13 participants, compared to initial SPM (dotted line) and target SPM (dashed line)*

in the *noise feedback - changing target* condition, deviations from target are mostly due to the second phase (target -15%) (see Table 3.3), which revealed to be hard to achieve for most of the participants.

Kruskall-Wallis H tests were performed to understand the link between the task responders and task non-responders groups and the questionnaires ratings. The results of Likert scales about effort, pleasantness and motivational qualities of each condition were compared across the responders and non-responders groups.

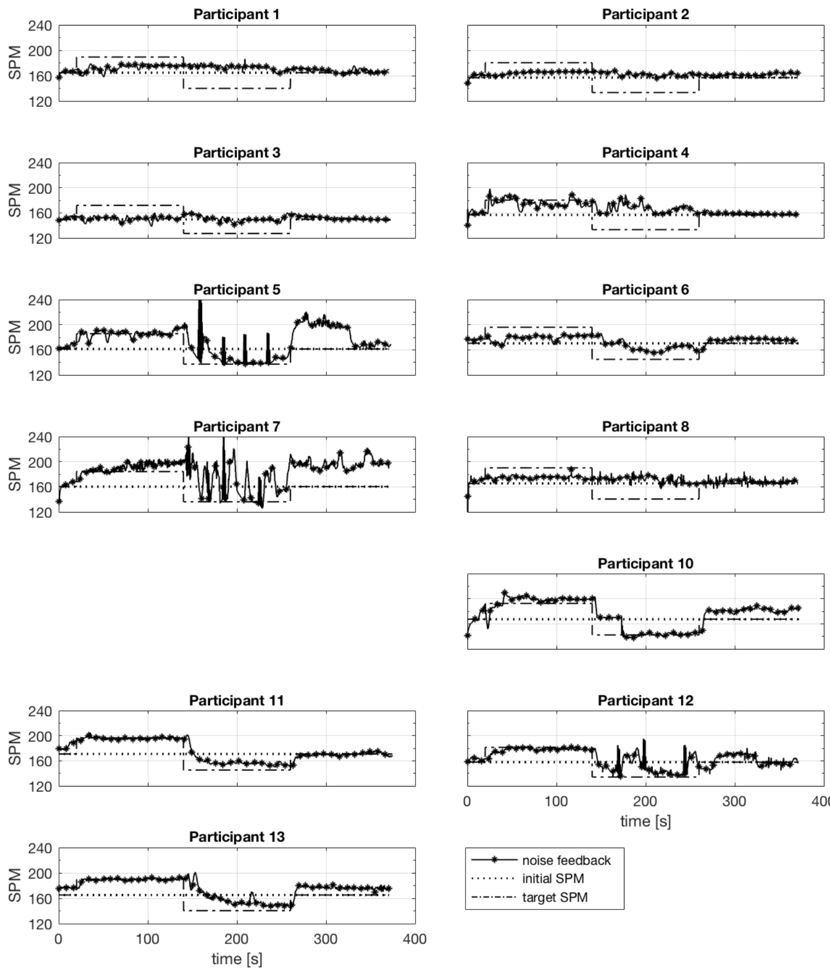


Figure 3.8: SPM time series in condition noise feedback - changing target *(diamond-marked line) for all 12 participants (participant 9 missing), compared to initial SPM (dotted line) and target SPM (dashed line)*

No significant difference between the groups was unveiled by the tests regarding perceived pleasantness, nor motivational qualities ($p > 0.5$). However, a tendency towards significance between the groups was found for required effort ($p = 0.067$). This effect can be explained by the fact that responders needed a higher effort (Mdn = 13, on a 6 to 20 Borg scale rating) in order to achieve noise minimization throughout the task, compared to non-responders who needed less effort (Mdn = 11). A Kendall's rank correlation tau test showed no significant difference based

target1	target2	target3
4.8%	18%	5.3%

Table 3.3: Average difference (in percentage) across all participants between mean SPM and target SPM for: target1, target2 and target3 in condition noise feedback - changing target

on gender on motivational effect (p = 0.068) nor effort (p = 0.082). However, due to the small group sizes there is low statistical power to draw conclusions among groups.

3.4 General discussion

3.4.1 Reinforcement learning in music-based sonification

The goal of the present paper was to develop an assistive auditory feedback system that can guide motor behavior. More specifically, we developed a music-based feedback system to manipulate the running cadence using a reinforcement learning paradigm (Maes et al., 2016; Silvetti and Verguts, 2012). In the traditional Pavlovian learning paradigm (Neumann and Waters, 2006), a stimulus appears as a conditioned stimulus (CS) that evokes no response in the direction of the wanted motor behavior. However, when paired with an unconditioned stimulus (US) that evokes an unconditioned response (UR), a conditioned response (CR) can be elicited. The US has biological significance and can elicit a defensive unconditional response (UR), such as avoidance behaviour, regardless of prior learning history (Neumann and Waters, 2006). In the classical Pavlovian approach, the US can be deleted after successful pairing. The CS will then evoke the (wanted) conditioned response (CR) on its own, until its effect gradually diminishes. Our approach differs from the Pavlovian approach in that we don't pair the pink noise (US) with the music (CS) in view of deleting pink noise and using music as conditioner for the conditioned response (CR). Rather, we use pink noise as a superimposed stimulus with music in order to create behavioral escape route to the unwanted noise. Both noise and music may thereby occur as unconditioned (US + US), although their valence is opposite. The two US are balanced in the sense that their quality and effect (cf. the rhythmicity of music) is related to unpleasantness (in the case of noise) and pleasantness (in the case of music). The balance between the pleasantness and unpleasantness of the two US forms the basis of our sonification strategy.

3.4.2 Design challenges

A major design challenge in our study was (i) to construct a feedback signal that would elicit the desired response for different participants, and (ii) to test whether the feedback signal can indeed modify motor behavior. We believe that the approach adopted here contributes to the call for methodic procedures for designing sonification strategies (Degara et al., 2015).

The design of the "good" feedback signal was based on three different types of noise that were superimposed onto the music, quality reduction by means of downsampling the music signal, and volume reduction of the music. A perception task indicated that pink noise was the best feedback signal. Accordingly, pink noise was used to refine its perceptual effect when used as a feedback signal during a simple running task. Once this feedback signal and its usage was designed and perceptually tested, we could use it in a motor behavior validation test. The validation test aimed at figuring out whether the pink noise auditory feedback signal could effectively alter motor behavior. We superimposed the pink noise feedback signal on top of the music, according to the reinforcement learning paradigm. By doing this we intended to drive the motor behavior in a particular direction. More specifically, we tested whether we could change the running cadence (expressed in SPM) up and down 15%. We know that this change of 15% in step rate is relatively high. Nevertheless, this was put forward as validation test for our sonification approach. The results suggest that the sonification strategy can indeed change participants' cadence up to plus or minus 7% of the initial spontaneous running cadence, and that the effect of the continuously provided embodied sonification is larger than the effect of a single verbal instruction to change cadence. However, there are responders and non-responders to the task and it is likely that the percentages of each are about 50%.

3.4.3 An embodied sonification strategy

Our sonification approach may be called “embodied" because the approach is based (i) on unconditioned signals that have biological signification in the sense that they elicit avoidance behavior, and (ii) on the motivation-reward system that deals with the unpleasant/pleasant aspect of the nature of those signals. Strictly speaking, one may argue that an embodied feedback would imply that the auditory signals' relationship to motor coordination is based on an enactment process, which is a process that heavily draws on prediction processing in such a way that it elicits agency (or feelings of control) (Leman, 2016). While the enactive approach was a strong motivator for the development of our sonification strategy, we realize that prediction processing and enactment may not play a dominant role in the user's responses to our sonification strategy. The psychoacoustic quality of music may draw upon a strong biological desire to get clear signals from the environment, but it is not clear how the psychoacoustic quality relates to enactment. However, due to the fact that the psychoacoustic quality is manipulated by pink noise superimposed onto the music, we still have the musical stimulus as a source for enactive responses.

Overall, the important issue related to embodiment is that the (unconditioned) psychoacoustic-based pleasantness taps into the motivation-reward system during processing. As known, the motivation-reward system is a mesencephalic dopamine system that plays a crucial role in reinforcement learning and error-related negativity (Holroyd and Coles, 2002). Our basic insight, learned from this study, is that it is possible to design a sonification strategy that offers a motor behavioral escape route to unpleasantness. And when this happens, a reward occurs because (i) unpleasantness disappears, and (ii) pleasantness appears (as music is by itself experienced as pleasant) (Berridge and Kringelbach, 2008; Vuust and Kringelbach, 2010). Obviously in this paradigm, the user's task is to find the motor behavioral escape route that turns psychoacoustic unpleasantness into psychoacoustic pleasantness. Not all users are capable of rapidly finding the escape route. It may be necessary to know if users have a natural sensitivity to music-based interactions. However, it is not excluded that this sensitivity can be learned and developed.

3.4.4 Effective, intuitive and pleasant sonification

Overall, we believe that the following main criteria for the proposed sonification are met, namely, effectiveness, intuitiveness (no need for instructions directly coupled to gait parameters), pleasantness (at least not disturbing), rewarding. Results unveiled that the proposed feedback was effective because it is able to alter running cadence by approximately 7% on average, without specific instructions. A similar increase in running cadence has been found by visual cueing (Willy et al., 2016). In addition, the approach is intuitive in the sense that the proposed pink noise feedback strategy performed significantly better than verbal instructions. The embodied foundation of this intuitiveness suggests a possibility for using such a system in self-training and gait re-training programs without the need of external assistance. A typical problem related to non-speech auditory alarms is that in order to make the alarm noticeable and provide sense of urgency, these are often loud and or highly distorted. This can be more harmful than helpful in some circumstance as it might disturb the subject cognitive activities (see Hermann et al., 2011, Chapter 19). This is also the case in motor learning activities as sports and motor rehabilitation, where an inappropriate auditory feedback could distract attention of the subject and hamper performances. In the design of the presented auditory feedback particular attention was paid to the tuning of the acoustic parameters to the perceptual characteristics of the users. The aim was to move from a pure auditory alarm-like warning (Wood and Kipp, 2014), towards a more motivational feedback by exploiting the motivation qualities of music, in particular music synchronized with user movements (Karageorghis and Terry, 1997; Terry et al., 2012). Finally, central to the reinforcement learning paradigm is the idea that people can be motivated to exhibit desired behavior by associating a reward to this behavior (Maes et al., 2016; Silvetti and Verguts, 2012). In the presented study, the runner acts as to maximize the outcome reward through minimization of the noise. One member of the responders group spontaneously stressed the motivational properties of the sonification system by writing in the comments: "Very motivating task: Distracts in a positive way of the more boring running").

3.4.5 Assistive sonification for sports activities

Overall we believe that this study is in support of the hypotheses that human beings are sensitive to auditory information in their environment, even when no instruction is given to attend to that auditory information. Secondly, we believe that the finding supports the hypothesis that behavioral responses to auditory information can be regulated at an embodied level, disregarding cognitive involvement. Moreover, we believe that the psychoacoustic unpleasantness is an example of auditory information that confounds with biological mechanisms of reward processing. If unpleasantness is avoided, then the absence of unpleasantness combined with a good music signal quality works as a reward.

The positive outcome of the present study shed lights on the opportunity to develop reward-based feedback systems for non-instructed motor (re)training programs in ecological environments. These could be implemented as apps for portable devices and could be targeted to different running parameters. Future work will be dedicated to improvements of the feedback strategy. The implementation of time-varying feedback intensity over time could further exploit the reinforcement learning paradigm in a more adaptive manner to maximize user's reward and minimize annoyance. In a later phase, attempts will be made to move from an alarm-like feedback towards a more cognitive sound-based approach through sonification of kinematic parameters.

My main contribution is: development of the sonification system and help writing the paper.

4

Tibial shock reduction by means of music-based biofeedback in over-ground running: proof-of-concept

Pieter Van den Berghe, Valerio Lorenzoni, Rud Derie, Joren Six, Joeri Gerlo, Marc Leman and Dirk De Clercq

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Abstract

Gait retraining by means of simple auditory biofeedback on tibial shock has become a method for managing impact loading in distance runners. However, this gait retraining approach has been limited to treadmill running. To provide proof of concept that over-ground retraining is effective for tibial shock reduction, 10 runners with high tibial shock (11.1 $\pm$ 1.8 g *) ran for a total of 20 minutes at ~3.2 ms^{-1} on a tartan track while actively listening to music-based feedback on their shock level in real-time. The music was synchronized to step frequency and distorted according to the momentary shock level, resting on a reinforcement learning paradigm. An over-ground retraining session with real-time biofeedback was* *enough to decrease the tibial shock by 3 g or 27% (p = 0.001, Wilcoxon signed-rank), and this without guided instructions on gait modification. Furthermore, the running speed remained stable, having no confounding effect on the shock magnitude. The running cadence did not substantially increase on group level within a session, suggesting personalized kinematic responses for lower impact running. These findings show the potential of wearable biofeedback systems that eliminate the need of exclusive retraining in laboratory and clinic settings, allowing to retrain runners in more natural environments.*

4.1 Introduction

Lieberman et al. (2010) considered running most injurious when the foot collides with the ground. Each footfall gives rise to a shock that reaches several times the gravitational constant (g) during sub-maximal, over-ground running (Van den Berghe et al., 2019). This shock is typically measured unidirectionally at tibial level as the axial peak tibial acceleration (APTA) (Van den Berghe et al., 2019; Morgan et al., 2015; Wood and Kipp, 2014; Clansey et al., 2014; Crowell et al., 2010; Crowell and Davis, 2011; Davis and Futrell, 2016; Bowser et al., 2018). High APTA has been related to an increased likelihood of having developed tibial stress fracture when rearfoot runners were tested in over-ground setting (Milner et al., 2006). When such an injury develops, spontaneous healing seldom occurs without load modification (Warden et al., 2014). Often, injured runners are forced to partially or fully refrain from their regular training volume. However, instead of lowering the training volume to prevent or manage the development of tibial stress fracture, altering the movement pattern towards a running technique generating less loading of the musculoskeletal system upon initial foot contact can be an alternative. A recent gait retraining study found a 62 % lower risk of running-related injury in novice runners who were retrained to generate less impact loading on treadmill compared to controls (Chan et al., 2018). Additionally, the regression model of Milner et al. (2006) indicated that for every 1 g decrease in APTA, the likelihood of having a history of injury decreased by a factor of 1.4.

Instead of explicitly imposing a pre-defined change in the running technique, such as verbal instructions for a foot strike alteration (Giandolini et al., 2013), various gait retraining studies have focused on lowering peak tibial accelerations by spontaneous self-adaption to real-time biofeedback. The advantage of spontaneous self-adaption is that runners find their own solution to the changes needed in the running technique. A systematic review indicated that running retraining sessions executed on treadmill through augmented feedback on APTA were effective for its reduction (Napier et al., 2015). Within a single session, biofeedback on APTA consisted of a real-time stream of the axial tibial acceleration on a monitoring screen in front of a treadmill. This type of feedback could minimize the level of impact loading measures in 4 out of 5 runners in a lab setting (Crowell et al., 2010). This feedback concept was further developed by Wood and Kipp (2014), providing auditory biofeedback on the peak tibial acceleration's norm during treadmill running. By providing pitched 'beeps' scaled relative to a runner's baseline peak tibial acceleration in real-time, they managed to lower two-dimensional peak tibial acceleration by about 0.7 g. Such simple auditory biofeedback was found to be equally effective in shock reduction compared to visual biofeedback displaying continuous accelerometer data (Morgan et al., 2015). In a multi-sessions (6 times 20 minutes) retraining program on treadmill, visual (traffic lights) and auditory (pitched beeps) modalities of biofeedback were simultaneously provided to runners bearing high APTA, and resulted in an APTA reduction of 3.3 g (-31 %) (Clansey et al., 2014). All these lab studies showed that biofeedback-based gait alterations towards running with less impact loading are feasible, paving the way to gait retraining in real world running settings.

However, running modification or retraining best happens over-ground because the mechanics while running on treadmill are not equal to over-ground running (Nigg et al., 1995; Chambon et al., 2015). Besides, most runners prefer to run outdoors. The proven effectivity of auditory biofeedback enables over-ground usage of biofeedback in natural environments. Development of an auditory wearable biofeedback system for use outside of the laboratory environment would therefore help advance gait retraining in an ecologically valid way. Simple auditory biofeedback, for example through beeps or sharp pitches when exceeding the targeted threshold, may be perceived as unpleasant or disturbing. Recent theories and experimental evidences (Maes et al., 2016; Bergstrom et al., 2014) hold that the use of music as biofeedback provides a valid alternative to standard cognitive sonification methods, thanks to its intrinsic reward characteristics (Salimpoor et al., 2015). Furthermore, the use of music for running adaptation fits well in the context of distance running as about half of the recreational runners regularly train with music (Van Dyck et al., 2015). Based on the above considerations, a wearable accelerometry system measuring APTA in real-time was developed (Van den Berghe et al., 2019). The system was proven reliable both within-session and between-sessions and can furthermore serve to generate auditory feedback that rests on music-based reward mechanism (Lorenzoni et al., 2018). This opens the possibility to evaluate if runners bearing high impact loading, and thus at risk for impact-related overuse injuries, are able to reduce the cyclic shock experienced by the lower extremity by means of a runner-friendly form of auditory biofeedback.

We present the proof-of-concept study involving a single session of running retraining by means of a wearable music-based biofeedback system and hypothesized that runners exhibiting elevated APTAs are able to reduce their level of tibial shock during over-ground running.

4.2 Methods

4.2.1 Participants

Ten at risk runners with high APTA were recruited from a Flemish running population. An a priori power analysis (GPower Faul et al., 2007, with α= 0.05, effect size of 1.5, paired testing) was conducted to estimate the required sample size (n=7). The effect size was based on the results of a treadmill-based gait retraining program including runners experiencing elevated APTA Crowell and Davis (2011). To qualify for the study, a runner had to bear an average APTA in either limb of one standard deviation above the mean APTA of the 88 screened runners (cf. 'initial screening'). The first 5 male and 5 female participants who met this criterion and agreed to participate took part in the biofeedback intervention session. Participants were at least 6 months injury-free (Yamato et al., 2015). They ran at least 15 km/week in non-minimalist footwear distributed over minimally 2 sessions at the time of the study. Training habits were questioned (Table 4.1). All participants signed a legally approved informed consent approved by the ethical committee of the Ghent University hospital, called Bimetra. This specific study has been approved under file number 2015/0864. The methods were carried out in accordance with their guidelines and regulations in order to publish the information/image(s) in an online open-access publication.

Variable	Mean	SD	Range minimum	Range maximum
Body height (m)	1.70	0.07	1.59	1.79
Body weight (kg)	67.7	7.4	56.2	82.1
Age (year)	33	9	24	49
Training volume (km/week)	29	12	15	50
Training speed (ms^{-1})	2.88	0.31	2.36	3.33

Table 4.1: Participants' characteristics: anthropometrics and self-reported training habits.

4.2.2 Research design

Two over-ground running sessions were completed in the runner's regular sportswear at a speed of 3.2 ± 0.2 ms^{-1} instrumented with the wearable accelerometry system developed for real-time identification of and auditory biofeedback on APTA. First, the runners with high APTA were identified during a screening session (October 2017 - February 2018) in laboratory settings. Then, an intervention session (January - March 2018) with auditory biofeedback on APTA took place at an indoor track-and-field site. Days between the sessions ranged from 59 to 138 (89 ± 28, mean $\pm$ SD).

4.2.3 Initial screening

Set-up

The standing subject was instrumented with a stand-alone backpack system connected to two lightweight, tri-axial accelerometers (LIS331, Sparkfun, Colorado, USA;1000 Hz/axis) fitted in a shrink socket (total mass less than 3 grams) to bilaterally measure tibial acceleration (Van den Berghe et al., 2019). Tibial skin was pre-stretched by strappal tape at ~8 cm above the left and right medial malleolus in the vertical and transversal planes to minimize unwanted oscillations of the skin during impact. The vertical axis of each accelerometer was visually aligned with the lower leg's longitudinal axis.

Procedure

An initial 5 minutes warm-up period was given along an oval track (circa 32-m length x 5-m width) which also served as habituation to the instructed speed, the measurement equipment and the environment. Participants subsequently ran for circa 20 minutes. The running speed was monitored on a trial-by-trial basis by timing gates spanning 6-m near the middle of a straight section. Five satisfactory trials of each foot were collected for processing. Trials were discarded if the running speed fell outside the set boundary of 3.2 ± 0.2 ms^{-1}, which is a standardized but common speed range to evaluate endurance running (Van den Berghe et al., 2019; Chan et al., 2018; Giandolini et al., 2013; Creaby and Smith, 2016; Busa et al., 2016).

Data processing

The tibial acceleration data were imported for signal processing via custom MATLAB scripts. The APTA of the first five foot contacts in the measurement area were averaged for each foot and per participant. The leg with the highest APTA value was considered.

4.2.4 Intervention

Set-up

The accelerometers of the wearable system were re-mounted on the participant's tibial skin as during the screening. A passive noise-cancelling headphone (HD25-ii, Sennheiser, Wedemark, Germany) was worn.

Biofeedback system

Auditory biofeedback used music and distortion to raise awareness of the momentary APTA level (Figure 4.1).

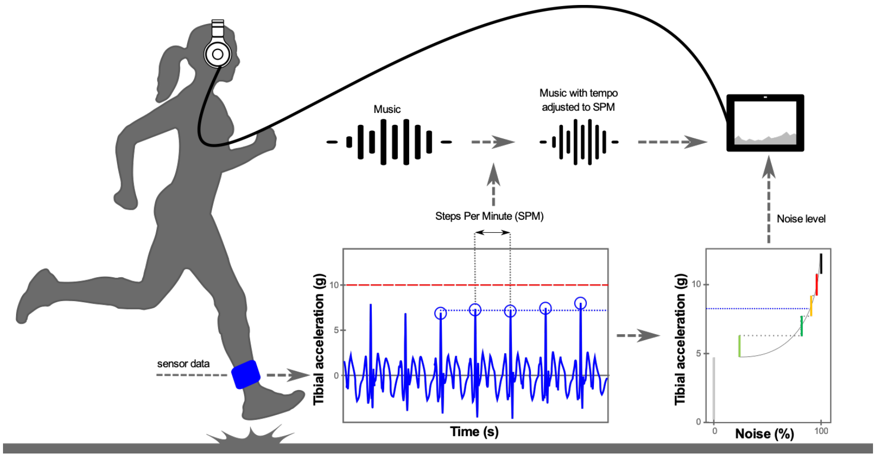

Figure 4.1: Schematic representation of the biofeedback system's main components for music-based biofeedback on axial peak tibial acceleration. An interaction loop of the smart music player generating biofeedback, continuously accounting for (in)voluntary alterations in running cadence by aligning the tempo (beats per minute) of the music to the cadence (steps per minute) of the runner. The red horizontal line indicates the baseline threshold of APTA. The five most recent values of APTA are averaged and mapped to a discretized level of noise loudness.

A peak detection algorithm continuously detected the APTA of each leg in real-time by means of a custom-build JAVA program operating on the backpack system (Van den Berghe et al., 2019). A peak was detected every time the axial acceleration exceeded 3.5 g with no higher axial acceleration value measured in the next 375 ms. The magnitude and timing of each detected APTA were transmitted through Open Sound Control to a custom build Max/MSP patch for music-based biofeedback. The auditory feedback consisted of a baseline music track with superimposed distortion of variable intensity, depending on the APTA level (for details about the feedback design see Lorenzoni et al., 2018). The music became distorted whenever the APTA level exceeded a pre-determined baseline threshold. The targeted threshold value in the present experiment was fixed to 50% of the runner's baseline APTA. The latter value was taken from previous gait retraining studies (Morgan et al., 2015; Clansey et al., 2014; Crowell et al., 2010; Crowell and Davis, 2011).

To account for biological step-to-step variability in APTA, the five last APTA values of the leg were averaged through a 5-point moving average (Clansey et al., 2014). That momentary APTA level was mapped using an empirically validated fitting to obtain a distinct level of noise loudness from Lorenzoni et al. (2018). Six loudness levels (0, 20, 40, 60, 80, 100% of noise) were created for good discretization, thereby accounting for inter-subject differences in the decoding accuracies (Saari et al., 2018). The noise loudness levels were calculated as a percentage of the music's root-mean-square amplitude level (i.e. 100% corresponding to noise with the same amplitude as the music's root-mean-square).

Music of a preferred genre (pop, rock, electronic dance, swing, world) was chosen by the participant. Because the habitual running cadence at sub-maximal speeds lies somewhere between 150-180 steps per minute, a music database consisting of songs with a clear beat in that tempo range was created. 77 tracks having a clear beat and correct tempo range were pre-selected. To prevent that the runner would adjust his or her cadence to the music's tempo, and based on the idea that interaction with music is empowering (Maes et al., 2016; Leman, 2016), we opted for a continuous alignment of the music's tempo with the runner's cadence (Moens et al., 2014; Moens and Leman, 2015). The beats per minute of any of the selected songs was continuously adjusted to the runner's steps per minute. Music tempi were manipulated up to $\pm$ 4 % of the instantaneous steps per minute without pitch shift (Lorenzoni et al., 2018). When a change in steps per minute exceeded this tempo shift for 8 s, another song started playing at a tempo that more closely resembled the altered running cadence. The momentary ratio of the runner's tempo (SPM) and the music's tempo (BPM) should then remain close to 1.

Procedure

Once bilaterally instrumented with the accelerometer, participants ran an initial 4.5 minutes at ~3.2 $\pm$ 0.2 ms^{-1}. Lap times were hand clocked to give verbal feedback on the running speed per lap. This warm-up period functioned as the no-biofeedback condition. In the software patch, the baseline APTA of the leg exhibiting the highest overall tibial shock was automatically determined for a sequence of 90 s (~ 1 lap of 289 m) in the middle of the no-biofeedback condition. Before the biofeedback condition started, the runners (i) were familiarized with the biofeedback by listening to the level of noise loudness going from minimum to maximum and vice versa; (ii) chose their preferred sound volume; (iii) chose their preferred music genre; (iv) received verbal instructions eliciting self-discovery strategies: "This may be very difficult but I would like you to try your best to concentrate on the task throughout the entire intervention. Listen carefully to the distorted music. Try to run with the music as clear as possible without any distortion at all. If impossible, keep the music distortion as low as possible by modifying your running technique. The amount of distortion is linked to your tibial shock. The music stops playing when the trial is over." Each runner was thus instructed to find a way to run with a lower level of tibial shock, however, no instructions were given on how to reduce the shock (Morgan et al., 2015; Wood and Kipp, 2014; Clansey et al., 2014). Biofeedback was provided for 20 minutes in total with rest of self-selected duration after 10 minutes. During the resting period the instructions were repeated. After completion, the runner reported the perceived exercise intensity [1 (very easy) – 10 (maximal effort)] based on the rating of perceived exertion scale (Seiler and Kjerland, 2006), and if they perceived any difference in the amount of distortion (yes/no). Three participants did not report their exertion level. Accelerometer data were continuously acquired during the no-biofeedback and biofeedback conditions.

Data processing

All detected APTAs were imported for processing using custom MATLAB scripts. The values of each individual were extracted for the time period of baseline APTA determination in the no-biofeedback condition. APTAs at the end of the biofeedback condition were extracted for an equal period of time. Extremely low peak values were inspected post-hoc. Inspection of the registered peaks revealed that the peak detection algorithm worked sub-optimally and sometimes detected false-positive peaks of low magnitude in the swing phase of the leg used for impact sonification. These values were post-hoc excluded from further analysis. False-positive peaks could be detected for removal using two exclusion criteria: (1) Step frequency should not differ more than 20 % from the average step frequency of the trial, (2) Step frequency should not differ more than 10 steps per minute from the contralateral foot for APTAs smaller than 4 g . If a faulty data point was detected, the previous as well as the next four data points were also removed. Namely, at those instances, the live biofeedback given to the participant would also have been faulty. In the no-biofeedback condition only one participant had to be corrected in this way, which resulted in a loss of 5% of the data for that participant. Two participants were corrected in the biofeedback condition, resulting in a loss of 1% and 3% of data for statistical analysis. A time period at the end of the biofeedback run was chosen for comparison alike previous research (Morgan et al., 2015; Wood and Kipp, 2014; Crowell and Davis, 2011; Creaby and Smith, 2016). Whereas previous research on running retraining averaged over just a handful of consecutive footfalls (i.e.. 5 to 20 footfalls), the retained APTA values belonging to the no-biofeedback (125 $\pm$ 10, mean $\pm$ SD) and biofeedback (129 $\pm$ 12) conditions were averaged to obtain a representative level of overall tibial shock per participant.

Running speed and cadence were included in the analysis because these variables can influence APTA (Van den Berghe et al., 2019; Busa et al., 2016). Morgan et al. (2015); Busa et al. (2016) and Baggaley et al. (2017) have reported that a substantial increase in running cadence at a steady-state running speed indeed lowered the magnitude of an impact loading measure. The average running speed was calculated for each participant using the lap times of the no-biofeedback and biofeedback conditions. The running speed was also determined for those laps corresponding to the extracted APTAs. To determine the running cadence, the time between sequential APTAs was used to estimate the steps per minute. The performance of the music-to-motion alignment is described by the ratio of the runner's tempo (SPM) to the music's tempo (BPM).

For further statistical analysis, the APTA, running cadence and speeds were averaged per participant for each condition. Wilcoxon exact signed-rank tests were used due to the low number of participants for the comparison of APTA, running speed and running cadence between the no-biofeedback and biofeedback conditions. APTA and cadence were tested one-tailed because there was a directional hypothesis. The Pearson correlation coefficient was calculated post-hoc between the session rating of perceived exertion reported by the runner and the difference in APTA to help explain some of the results. The alpha level was set at 0.05 (SPSS v25).

4.3 Results

4.3.1 Tibial shock

During the no-biofeedback period, the analyzed APTA was 8.9 to 13.6 *g* between-participants. The participants were able to reduce APTA by 26 % to 8.1 $\pm$ 1.9 g (p = 0.001, mean negative rank = 5.50, z = -2.81) by means of the music-based real-time biofeedback (Figure 4.2 **a**), and this without guided instruction on gait modification.

The APTA's distribution is shown for the average, most and least pronounced responder (Figure 4.3). While most shocks decreased in magnitude, few footfalls have an APTA that would still be categorized as high in these three runners.

4.3.2 Music-based biofeedback characteristics

During the biofeedback run, the momentary ratio of the runner's tempo and music tempo (SPM/BPM) was 1.00 $\pm$ 0.03. Indeed, the music's beats per minute was continuously aligned to the tempo of the runner's steps per minute. The level of noise loudness added to the synchronized music varied from maximum to zero on group level (Figure 4.4).

4.3.3 Spatio-temporal characteristics

Running speeds during the no-biofeedback and biofeedback conditions were respectively 3.15 $\pm$ 0.12 and 3.13 $\pm$ 0.15 m^{-1} (p = 0.520, z=-0.71). The running

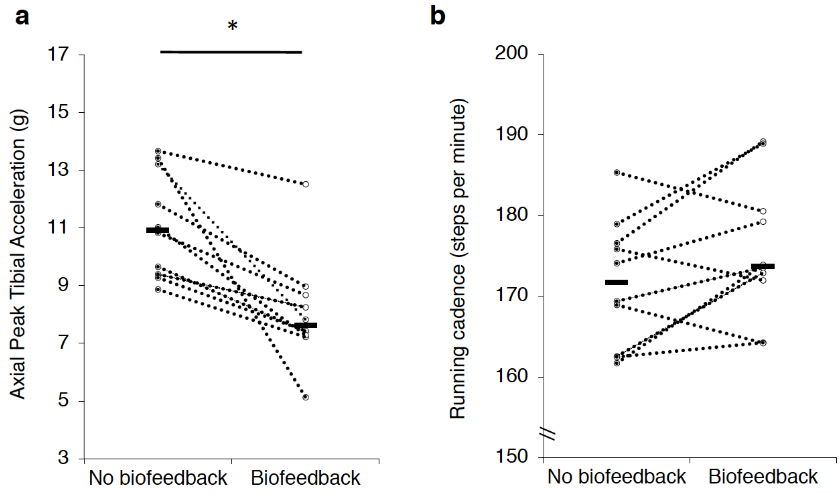

Figure 4.2: ***a*** *Axial peak tibial acceleration and* ***b*** *steps per minute for the [left] no-biofeedback and [right] biofeedback conditions. Each circle represents an individual's level of peak tibial acceleration in a condition. A short horizontal line indicates the median level of the variable of interest within a condition. * indicates* $p < 0.05$.

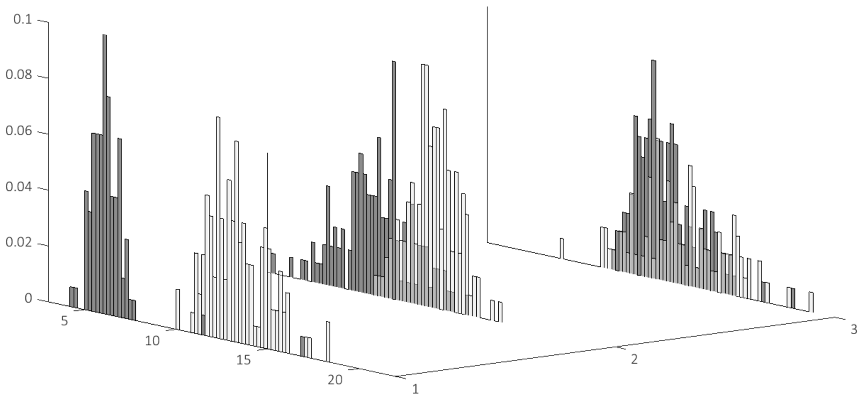

Figure 4.3: Histogram of analyzed APTA values during the no-biofeedback and biofeedback conditions for the maximal, average and minimal responders. The footfalls of each responder have been normalized to the number of footfalls of that participant counted in both conditions.

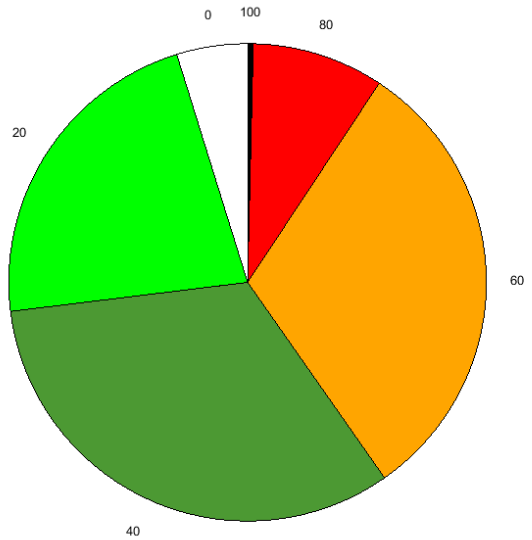

Figure 4.4: The proportion of the pink noise generated during the 20 minutes biofeedback run for the group of runners. Level 0 represents the 'music only' category without superimposed noise. The level of noise loudness added to the synchronized music has been subdivided into 5 categories. Each level of noise loudness corresponds to a level of tibial shock relative to the runner's baseline g-*value.*

speed for the laps chosen for APTA comparison did also not differ (p = 0.090, z = -1.72) and also remained within the a priori permitted boundary of $\pm$ 0.20 ms^{-1}. Consequently, speed had no confounding effect on the proportion of generated noise loudness nor on the pre-post differences in APTA. The group's steps per minute tended to increase (p = 0.053, z= -1.682, positive mean rank = +6.3).

4.3.4 Perceived exercise intensity

The mean session rating of perceived exertion was 4 (somewhat hard) with individual values ranging from 2 to 9. In this group of retrainers, the participant reporting the highest rating of perceived exertion also reported the lowest combined training volume and training speed. The perceived exertion did not correlate to the absolute (p = 0.530, r = -0.29) nor relative (p = 0.618, r = -0.23) decreases in APTA, implying that the attained level of exertion did not seem to influence the reduction in tibial shock achieved by these runners.

4.4 Discussion

The purpose of this 'proof of concept' study was to determine if APTA could be reduced through music-based biofeedback during an over-ground retraining session at a common running speed. Supporting our first hypothesis, runners with high APTA decreased their APTA by -26% or -3g while running at a controlled speed with real-time biofeedback generated by a wearable system. Whereas Wood and Kipp (2014) demonstrated the ability of simple 'pitched' auditory biofeedback to temporary reduce two-dimensional peak tibial acceleration by less than 1g during treadmill running, this is the first study targeting at risk runners who achieved a reduction in tibial shock by means of unimodal biofeedback in an over-ground setting, and this without direct instructions on gait modification but due to strong auditory-motor coupling. Clansey et al. (2014) found a decrease of 3.3 g after multiple retraining sessions at 3.7 ms^{-1}in runners with high APTA. That decrease corresponds to what we found at the end of a single retraining session at the slightly lower running speed of ~3.2 ms^{-1}. The runners in this study could all achieve shock reduction by means of music-based biofeedback.

It is debatable whether an extreme target of minus ~50% in APTA, as in previous research (Morgan et al., 2015; Clansey et al., 2014; Crowell et al., 2010; Crowell and Davis, 2011; Bowser et al., 2018; Creaby and Smith, 2016), is required in a gait retraining context. This target was hard to achieve or maintain as it was only reached 4.8 % of the retraining time in this group of high impact runners. The quote "I heard several noise levels but never heard music without noise" of a participant illustrated this finding. Even the maximal responder was not able to completely remove the superimposed noise (run only on music) for the majority of the time. A more realistic target for the targeted population seems to be -30% (circa -3 g) in APTA, which will also reinforce the reward of running with non-distorted music. This stems with the recent finding of runners experiencing high APTA that were able to achieve and maintain a reduction of about 30% in APTA after completing a retraining program in the laboratory (Bowser et al., 2018). A lower target may also counteract the slight discomfort (i.e. gait felt unnatural) reported by several participants at the end of the run. A multi-session program is likely required for a natural feeling of the newly adopted gait pattern (Crowell et al., 2010). Assessment of motor retraining was however beyond the scope of this study since about 6 to 8 sessions are required to enhance any retention of the alterations in the movement pattern (Clansey et al., 2014; Crowell et al., 2010). Randomized controlled trials should determine if adherence to more pleasant auditory biofeedback also results in an altered running technique that becomes motorically grinded.

The findings of the present study are applicable to runners capable of running 25 min at circa 3.2 ms^{-1}. They were able to decrease their overall APTA, with a decrease not correlated to their session rating of perceived exertion. Shock reduction is thus achievable in a heterogenous group of moderately-trained runners. Given that the session rating of perceived exertion is indicative of the exercise intensity (Seiler and Kjerland, 2006), we estimate that the retraining session was generally performed near the first ventilatory threshold. At such exercise intensity, inter-subject responses varied (Figure 4.2 and Figure 4.3). Tibial shock reduction was namely not accompanied by a substantial increase in running cadence on a group level. Besides, 5 out of 10 runners commented to have tried a non-rearfoot strike though only 1 runner stated to have maintained a forefoot landing. This all suggests inter-individual kinematic changes. Other, grouped movement features may thus be more important than step frequency alone to modulate the unidirectional tibial shock. Future research may verify this hypothesis.

The study was performed at one standardized testing speed, which is common practice in running research (e.g. Clansey et al., 2014; Milner et al., 2006). The instructed running speed may affect results since it influences the absolute magnitude of APTA and the instantaneous vertical loading rate (Van den Berghe et al., 2019). Nonetheless, Chan et al. (2018) showed that the vertical loading rate after gait retraining was significantly lowered at multiple running speeds. Chan et al. (2018) also reported less running-related injury in novice runners after completing a treadmill-based gait retraining program that reduced the instantaneous vertical loading rate of the ground reaction force when tested at 3.3 m^{-1}. Given that this loading rate correlates to APTA (Van den Berghe et al., 2019), usage of the music-based biofeedback system resulting in substantial impact reduction may therefore have clinical implications for injury reduction and management strategies of impact-related running injuries in over-ground settings.

In conclusion, music-based biofeedback with impact sonification provided by a wearable system becomes an option for an over-ground gait retraining approach. The provision of auditory information on likely clinically relevant biomechanical data via a wearable biofeedback system eliminates the need of exclusive retraining in laboratory/clinic settings, thus allowing retraining in more natural environments. As such, this manner of retraining could be easily implemented by runners, given some technical improvements (e.g. wireless accelerometer connected to a miniaturized processing device) and given adequate speed control, in their regular training environment.

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

5

The sonic instructor: a music-based biofeedback system for improving weightlifting technique

Valerio Lorenzoni, Jacob Staley, Thierry Marchant, Kelsey E. Onderdijk, Pieter-Jan Maes and Marc Leman

In *PLOS One*, 2019

Abstract

In this study, we assumed that correct functional movements for weight lifting can be learned with the help a music-based biofeedback system. We focus on one specific movement called deadlift, and we compared musical feedback with verbal feedback from experienced trainers. Physical parameters under consideration were the spine (loss of midline stability resulting in flexion) and the forward displacement of the barbell during the repetitions relative to the mid-foot. Experiments were carried out with two independent groups, verbal feedback versus music-based feedback. We recruited 31 recreational weight lifters, of ages comprised between 21 and 42 years. Comparison with respect to an initial control condition revealed that both feedback types are effective in improving the movements

for the deadlift. No significant differences were found across the two feedback types, neither in terms of movement nor in terms of clarity and motivational. The results suggest that the proposed feedback system is a valid tool for technology-aided training and self-training practices.

5.1 Introduction

Biofeedback has been used in the domains of sports (Petruzzello et al., 1991; Onate et al., 2001), motor rehabilitation (Tate and Milner, 2016; Isakov, 2007), and even neurological rehabilitation (Huang et al., 2006). Biofeedback provides information about physiological and/or biomechanical parameters related to the performance (Giggins et al., 2013). Typically, the main goal of such systems is to enable subjects to improve their performances without the explicit instruction of a trainer or therapist. Often biofeedback provides information after the performance of a task. However, due to recent technological developments it is possible to provide real-time biofeedback in a continuous way during the performance. Traditionally, the feedback is presented via screens (visual feedback), loudspeaker/headphones (auditory feedback), or vibrotactile devices (tactile feedback) (Sigrist et al., 2015; Alahakone and Senanayake, 2009). In this paper, we describe the design and validation of a real-time bio-mechanical auditory feedback system for a weightlifting movement called: *deadlift*. Over time, weightlifting has become increasingly popular, and more recently it gained worldwide exposure from the fitness regimen of CrossFit. Although researchers have proven the benefits of such functional weightlifting movements (Smith et al., 2013), clear knowledge of the exact technique is required in order to maximise movement efficiency and minimise the risk of injury.

The deadlift is one of the three possibilities in powerlifting. The deadlift presents a unique set of challenges for proper execution that allow for a succinct set of attributes to be monitored and reinforced. Further, the deadlift presents a safety risk with regards to the spine. The risk arises due to the required hinging motion at the hip, and subsequent loading of the posterior musculature and spine, in order to perform a full repetition. The deadlift consists of grasping a barbell from the resting position on the floor, raising the weight by extending the knees, hips, and back while holding the arms downward. On completion of the movement, the knees must be locked in a straight position and the shoulders retracted. A detailed description of the technique can be found in Bird and Barrington-Higgs (2010). There exist a total of eleven variations of deadlift movements as reported by Bird and Barrington-Higgs (2010) and Escamilla et al. (2000). However, the ones mostly used by athletes are the so called: conventional and nonconventional styles (i.e. sumo). McGuigan and Wilson (1996) investigated the biomechanical differences among the last two techniques and highlighted the advantages of the sumo technique in terms of posture and barbell due to the wider foot stance. In the present study we focus on the conventional style of deadlift, which is mostly used in functional fitness programs (e.g. CrossFit). Due to the fact that the deadlift is a closed chain exercise (i.e. feet in constant contact with the ground), it is often used in the prevention and rehabilitation of anterior cruciate ligament (ACL) re-construction to improve strength of the muscular structures that surround the knee and hence dynamic stability of the joints. However, improper technique during deadlift lift-off phase (i.e. the beginning of the movement) may predispose the spine and back musculature to an increased risk of injury (Granhed et al., 1987; Cholewicki et al., 1991).

Risk of injury is typically related to two main faults in performing the movement, that is, improper spine alignment and barbell path. The fault with respect to the spine is typically a loss of neutrality (i.e. excessive flexion) due to the demands of the external load of the barbell. This creates an undesired outcome by placing a greater proportion of the load on the lower lumbar of the spine, as opposed to being distributed across a range of supporting musculature. The fault with respect to the barbell path has the same potential deleterious consequence, placing a higher demand on the lower lumbar, and increasing the risk of injury. Under proper movement the barbell should travel up the torso while maintaining a vertical line centred over the middle of the foot. Typically, deviation from this path occurs with the barbell drifting over the toes due to the force of the external load. Increased horizontal distance of the barbell relative to the hinge point (i.e. hip) translates to an increase in the moment arm, which once again places higher demands on the lower lumber of the spine, and where the common fault of excessive flexion of the spine occurs.

The presented system aims to provide real-time musical feedback based on a sonification of movement performance. The movement quantities being sonified, and on which the participant gets feedback, are the spine curvature and the barbell horizontal displacement, as these quantities are directly related to increased risk of injury. Usually coaches spend time in the first phase to teach the right technique and provide feedback to the performers. However, having continuous feedback by a coach is not feasible while training in public gyms or at home. Therefore there is a need to develop (portable) systems that are able to guide athletes towards the correct movement patterns, thus offering the opportunity to develop a proper and safe technique.

Sonification of weightlifting movements has been shown to increase average exertion of power compared to silent condition (Murgia et al., 2012). However, it has not been used for improving the technique, nor for injury prevention. In our study, sonification is meant as a manner of steering the correctness of the movement without explicit indication by verbal cues from a human trainer, thereby laying the ground for safe movement habits and thus for injury prevention. Our steering paradigm is based on reinforcement learning, the idea that subjects learn in order to maximise the reward of the outcome of their actions, and minimise the punishment due to unwanted outcomes of their actions. When coupling reward and punishment to a desired behavior, subjects are likely to learn to exhibit this behavior spontaneously, without needing to be told explicitly what to do. Reinforcement learning thus steers subjects' behaviour without telling how to act. Thereby, subjects have to find the proper solution for achieving the correct performance.

In this context, music is particularly relevant as it may be rich source of auditory reward and pleasure (Leman, 2016; Maes et al., 2016). Music was shown by several researchers to have positive effects during physical activities: enhance work output (Rendi et al., 2008; Edworthy and Waring, 2006) increase arousal (Karageorghis et al., 2010), and boost mood states (Shaulov and Lufi, 2009; Lim et al., 2014), especially when music is synchronised with the tempo of movement. In the present study, we use music and its sound quality as reward, whereas we use distorted music, that is, music with bad sound quality as punishment. Obviously, reward (through increasing the sound quality) is associated with correct movements, whereas punishment (through decreasing the sound quality) is associated with incorrect movements. More specifically, the unwanted movements (spine forward bending and barbell forward displacement with respect to initial position) cause a down-sampling of the played music track and a forward panning (and reduction in number) of the active loudspeakers.

Our hypothesis is that a music-based feedback system, working with reinforcement learning, could be comparable to the verbal instructions of a human instructor. We also assume that the sonified feedback would be more motivating than standard verbal instructions due to the reward mechanism and pleasurable effects of music. Participants were split into two groups upon arrival. The groups were balanced as much as possible in terms of sex and experience. One group received only verbal feedback and the other group only sonic feedback during 10 deadlift repetitions. We compared the movement parameter after feedback with a control condition without any feedback, taken as reference of the participant's initial movement patterns. To test our hypothesis the movement improvements with respect to the control between the two groups were compared.

The results suggest that the proposed auditory feedback system is a valid tool to improve athletes' deadlift skills and in general weight lifting technique.

5.2 Materials and Methods

5.2.1 Participants

Thirty-one participants (14 female) took part in the experiment. The age range was 20 to 42 years (mean = 29.2, sd = 5.7). All the participants were trained in sports. In particular, 11 participants mentioned to have more than 2 years of experience with deadlift movements, 15 between 6 months and 2 years and 5 declared to have less than 6 months of experience with it. The majority of participants (19) declared to mostly use music while training, 6 to train without music and 6 equally with and without music. Fourteen participants (45 %) declared to have received music education in their life.

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. All participants voluntarily participated; they were informed about the physical effort required for the experiment and that questionnaires could have contained personal questions. As compensation, participants received a voucher for a consumption at the library restaurant.

5.2.2 Apparatus

The experiment took place at the IPEM-IDLab Art&Science Lab in De Krook library in Ghent. The laboratory has dimensions: 10 m x 10 m x 7 m height and is instrumented with an immersive sound system of 64 speakers Martin Audio CDD6, distributed all around the room (two circles at different heights and on the ceiling). Eight Qualisys infrared cameras were used for the motion capture (Mocap) recordings. A male barbell (20 kg) with 2 x 5 kg weights was placed at the center of the room on two protective hard foam pads. The cameras detected passive reflective spherical markers of 2.5 mm radius. Participants were equipped with a full body markers set-up, consisting of a total number of 22 markers. Trousers with a fixed configuration of 6 markers were provided to the participants (two different sizes were made available). Two straps with a single marker were placed on the wrists; a headset with 4 fixed markers and adjustable width was used for the head. A total of 10 markers were attached directly on the skin of the participant, using a biocompatible double sided tape by 3M. Specifically, 4 markers were attached on the spine at the height of the vertebras: L4, T12, T7 and C2. The larger spacing between the last two markers was chosen to account for the presence of sport tops used by female participants. Markers were also attached on the elbows, shoulders, and on the front part of the feet. Four markers were placed on the barbell: two at the extremities and two on the clap next to the weight on one side only. Asymmetry was chosen to improve barbell model recognition. See images in Fig. 5.1 for visualization of the full positioning of the markers.

Mocap recordings were performed on a dedicated Windows computer. The system evaluated the 3D markers positions at a frequency of 100 Hz. These position were transmitted in real-time as OSC message to a custom-build Max4Live patch implemented as audio effect within Ableton Live. The Max4Live patch was responsible for starting and stopping the music, providing the sonification based on the physical parameters, and storing the data.

The Max4Live patch calculated the following quantities, used for both analysis and sonification.

Spine bend. The sum of the consecutive euclidean distances between spine mark-

Figure 5.1: Mocap markers positioning

ers:

$$spine\ bend = d0 + d1 + d2$$

This length is directly linked to the spine bending, which is the physical parameter we tried to optimize for injury minimization, and therefore named spine bend.

Barbell-foot (B-F) distance. The horizontal component of the distance between the line connecting the extremities of the barbell and the markers on the front part of the feet. The smallest of the two distances was considered.

See Fig. 5.2 for a schematic visualization of the above quantities.

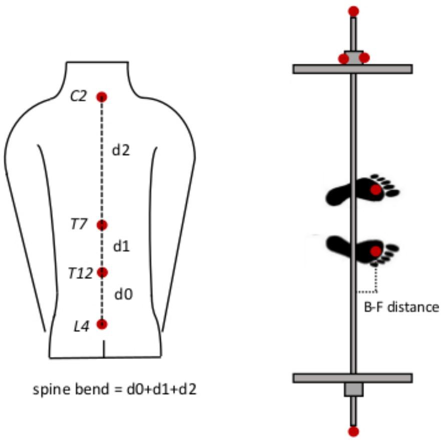

Figure 5.2: Sketch of the derived measured quantities: spine bend (left) and barbell-foot distance (right). The circles represent the reflective markers.

5.2.3 Experimental procedure

Once in the lab, participants received a written description of the experiment. They were asked to sign an informed consent form and fill in a questionnaire with general information about sex, age, level of experience with weightlifting, music education, injuries. Subsequently, a video was shown of an expert performing 10 deadlifts, in front and side view. It was explained that the focus of the experiment was on the neutrality of the spine during the movements and verticality of the barbell path.

Participants were then equipped with the markers set-up. The Qualisys software made use of a pre-trained skeleton model to recognize the body parts across different participants. A separated model for the barbell was used. The correct labelling of markers was checked at this stage.

One of the authors is a certified Level 2 Crossfit trainer and functioned as the instructor during the experiments. A warm-up routine was provided by the instructor to all participants prior to the tests. At this point reference parameters for each participant were recorded.

Neutral spine. Participants were asked to grab the bar standing and keep the back in unloaded neutral position.

Max spine bend. Participants were asked to grab the bar on the ground and slightly bend the back upwards. The instructor helped them find this incorrect position, corresponding to the maximal deviation from target movement.

Initial B-F distance. Participants were asked to grab the barbell on the ground as if they would start the movement and place it approximately in the middle of the foot. The initial distance between the barbell and the feet was then recorded.

Based on these values the Max4Live patch calculated in real-time the following non-dimensional quantities, which are used for the analysis:

- non-dimensional spine bend (*sb*),

$$sb = \frac{spine\ bend - neutral\ spine}{max\ spine\ bend - neutral\ spine}$$

  ,

- non-dimensional barbell-foot distance (*bfd*),

$$bfd = \frac{BF\ distance}{initial\ BF\ distance}$$

.

Participants were informed that, to perform a correct movement, the spine would have to remain in the measured neutral position throughout the movement and that the barbell would have to remain at the same distance from the toes as measured by Initial B-F distance to ensure verticality of the barbell path.

The actual tests started with a serie of 10 deadlifts at own tempo, middle-low pace. This was taken as *control condition* for the analysis. Subsequently, participants were split into two groups, as homogeneous as possible in terms of sex and experience level. Experience level was based on the information provided by participants at the beginning of the session while compiling a general questions form. Participants were requested to select among three options about experience level: “less than 6 months” ,“between 6 months and 2 years” , “more than 2 year”. These were labeled as level A, B and C, respectively and used as ordered factors in the analysis. Specifically, the instruction group consisted of 2 level A participants (1 male and 1 female), 9 level B (4 female and 5 male), and 5 level C participants (2 female and 3 male). The sonification group consisted of 3 level A participants (3 male), 6 group level B (4 female and 2 male), and 6 level C participants (3 female and 3 male). Posterior analysis of homogeneity of these parameters among the groups by χ^2 confirmed homogeneity ($\chi^2(2)$ = 1.778, p = .411). One group of participants received verbal feedback by the instructor, while the other group received sonification as feedback. The groups are hereafter called *instruction group* and *sonification group*, respectively.

Participants of both groups were asked to perform 10 deadlifts for each of the following points of performance: *spine*, *barbell* and *combination*. The points of performance were chosen to ensure the participant performed the movement with safety and efficacy in mind. The first two points of performance were randomized across participants, while the *combination* was always last. Participants were instructed to only focus on the specific performance point, and informed that continuous feedback (either as verbal instruction or as sonification) would be given only if the movement deviated from correctness for the specific point of performance under analysis.

In particular, concerning the spine, feedback was only provided if the spine curvature was positive (i.e. increased distance between spine markers, *sb* larger than zero), meaning forward bending, as this is directly responsible for increasing load on lower lumbar spine. Concerning the barbell-foot distance, feedback was only provided if the barbell moved towards the toes during the movement (i.e. *bfd* approaching zero) as this would increase the momentum on the back and increase the risk of injuries.

Hereafter, the explanations provided to participants, respectively for the *instruction group* and the *sonification group* and for the specific point of performance, are reported.

Instruction feedback. In this case the instructor informed the participants as follows:

Spine : "You will receive feedback when your spine deviates from the neutral starting position. You will focus on maintaining your neutral spine position during the movement, as well as keep your shoulders retracted. The two cues you will hear are 'straight spine' and 'shoulders back' as an instruction to correct these faults."

Barbell : "You will receive feedback when the bar path deviates from the vertical line of your mid-foot. You will focus on maintaining a vertical path of the bar throughout the movement by maintaining a vertical shin and keeping the bar close to your shins, thighs and torso during the progression of the movement. If the horizontal distance of the bar from your body increases, the cue you will hear to correct this is to 'keep the bar close', which is a reminder to engage the lats and force the barbell back to the body. The second cue will be 'knees back', which is instruction to drive your knees back to create vertical shins."

Combination : "You will receive feedback on both points-of-performance, which are correct spine position and barbell path. The cues you will hear will be the same as before."

Sonification feedback. The feedback in this case consisted of modifications of the base music track if the movement deviated from correctness.

Spine : " The music will be distorted when your spine curvature deviates from the initial neutral position we measured. Try to improve the music quality by improving your spine curvature. You can hear the effect if you try to bend your spine."

Barbell : " The audio configuration will change if the barbell path deviates from verticality. Try to improve the music quality by focusing on the barbell path. You can hear the effect if you try to move the barbell towards the toes."

Combination : " This is a combination of the previous two audio modifications. Try to pay attention to both parameters."

After each series of repetitions, a break of 5 minutes was introduced to enable the participant to recover sufficiently. During the break they were asked to fill out a Rating of Perceived Exertion (RPE) questionnaire (Borg, 1998) and indicate how heavy the effort had been during the exercise, ranging from 6 (" no exertion at all") to 20 (" maximal exertion"). In order to test the differences in motivational properties of the feedback, participants also performed a modified version of the

Brunel Music Rating Inventory 2 (BMRI-2) test (Karageorghis et al., 2006). In this test, they were asked to rate on a 7-point Likert scale: clarity, pleasantness, accuracy, motivational properties and usability of the presented audio feedback. All questionnaires were implemented as Google forms on a dedicated Apple computer within the same room, only used by the participants.

5.2.4 Stimuli

Music. In all conditions, the same music track was played. The piece was specifically composed for this experiment by the authors. The music was composed respecting the following requirements:

- to be unknown, to avoid personal affection,
- to be instrumental (no lyrics), to avoid focus on content,
- to have a clear beat, to stimulate repetitive movements.

Sonification. The sonification group received feedback on their movement performance through alterations of the baseline music track. Alterations were based on a non-linear mapping of the input physical parameters, according to the following logistic function:

$$y = 1 - \frac{1}{1 + e^{-\alpha*(x-\beta))}} \tag{5.1}$$

where x represents the physical variable to be mapped and α and β empirical parameters determined in a preliminary testing phase to ensure enough responsiveness of the feedback and margin for movement execution without distortion. More specifically, the implemented feedback mechanisms consisted of:

Spine bend feedback. Continuous variations of the sampling rate of the music track.

In practice, the non-dimensional spine bend value *sb* was mapped into the logistic function of Equation 5.1 with parameters: $\alpha = 10$ and $\beta = 0.2$. The resulting output value (comprised between 1 and 0) provided the input of the *degrade~* object implemented in Max4Live. This resulted in alterations of the actual sampling size of the audio buffer resulting in a “metallic sounding” distortion.

Barbell-foot distance feedback. Change in panning and number of effective speakers.

The *bfd* was mapped into Equation 5.1 with parameters: $\alpha = 15$ and $\beta = 0.6$. The output y in this case determined the gain of the Ableton master track right and left output channels, in counterbalanced order. The two stereo channels outputs of the Ableton Master track were mapped to different speaker configuration using the Dante Controller software by Audinate. The right channel was mapped to a speaker configuration surrounding the participant, while the left channel was mapped to only the 3 speakers in front of the participant. Consequently, if the value *bfd* moved towards 0 (i.e. barbell toward the foot) the gain of the left channel (linked to the three speakers in front only) was increased while that of the right channel (linked to the all surrounding speakers) was decreased. This implies volume reduction and directionality change, giving the participant the feeling that sound was only coming from the front.

The music track together with the Max4Live patches for music alterations, can be found and downloaded as Ableton project from the following repository: https://doi.org/10.5281/zenodo.3355107.

Data acquisition

The markers' positions were acquired by the Mocap system on the Mocap computer and streamed in real-time as OSC to the Max4Live patch on the control computer. The derived quantities *sb* and *bfd* were calculated by the same patch. Recordings were made every 10 milliseconds and stored as .txt file on the Windows computer running Ableton. The stored files contained the following quantities:

- 3D markers' positions
- *sb* and *bfd*
- distortion level (only for sonification feedback)
- right and left output channel volume (only for sonification feedback)

A separate file was stored for each participant and each point of performance. The questionnaire information was directly put into Google Drive.

Data analysis

The series of repetitions were split into single deadlift movements by analysis of the vertical barbell displacement using a custom Python script. The first three and last two repetitions were discarded in the analysis to minimize transient effects. One mean value of the measured quantities over five deadlift repetitions was calculated for each participant and each condition.

Our hypothesis is that our music-based auditory feedback would perform comparably to human instruction. To prove our hypothesis, the mean changes in movement with respect to the control condition after the feedback by the instructor and after the sonic feedback, were compared. More specifically, differences between the means of spine bend (*sb*) and barbell-foot distances (*bfd*) in the feedback condition and control condition (feedback - control) were evaluated for the instruction and sonification groups separately.

We hereafter refer to as "improvement in spine bending", a negative shift of the mean *sb* with feedback with respect to the mean *sb* in the control condition, which corresponds in practice to an average increase in spine backward extension. An "improvement in barbell-foot distance" is defined as an increased average distance of the barbell from the midfoot during the feedback session compared to the control session. This indicates that the barbell travels in a vertical path centred over the mid-foot, which stays closer to the body during the movement compared to the control condition.

Statistical analysis using the software R version 3.3.3, was performed on the differences between the instruction and sonification groups and for the different points of performance. Questionnaires information about clarity and motivational properties of the feedback for each point of performance were also analyzed.

5.3 Results

5.3.1 Performance distributions

Spine bend differences. Fig. 5.3 shows the distributions of mean performances across participants for instruction (left) and sonification (right) feedback. In this case, the shown points of performances are *spine* and *combination*, for which participants received feedback on the spine curvature. A value 0 indicates that mean spine curvature corresponded to neutral position throughout the deadlift repetitions. Negative values indicate backward extension and positive values indicate forward bending. The latter was corrected through feedback.

The values of the distributions of non-dimensional spine bend for all points of performance and control are reported in Table 5.1. Means and standard deviations are reported for the normally distributed variables, medians for the non-normally distributed ones. Results of statistical tests against the control condition are also reported. For the normally distributed variables t-test are used and t-values and significance p are reported. For non-normally distributed variables Wilcoxon tests were used and z-values and significance p are reported.

Comparisons of point of performance *spine* and *combination* with the control condition yield significant differences for both instruction (p = .0001 and p = .0007 for *spine* and *combination*, respectively) and sonification feedback (p = .018 and p = .005 for *spine* and *combination*, respectively). As expected, no significant difference with respect to control is observed for point of performance barbell as no feedback on spine bend is provided in the session for this point of performance.

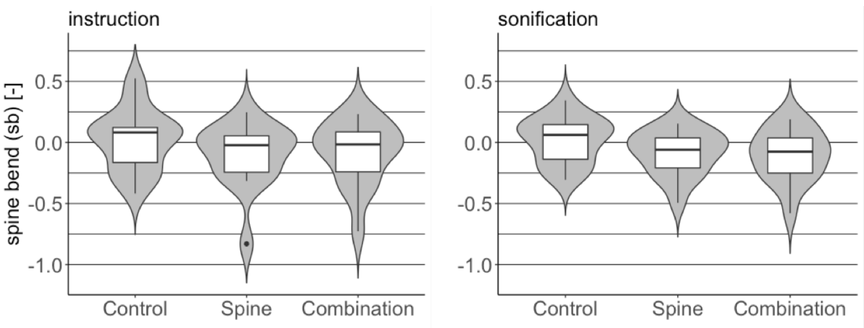

Figure 5.3: Non-dimensional spine bend distributions for points of performance spine *and* combination *and control condition. Instruction group (left plot) and sonification group (right plot).*

Barbell-foot distance differences. The distributions of the *bfd* are shown in Fig. 5.4 and summarized in Table 5.2. In this case a value 1 indicates that the mean barbell-foot distance was equal to the initial measured barbell-foot distance throughout the deadlift repetitions. Values larger than 1 indicate bigger mean distance barbell and toes than the initial measured distance and negative values indicate mean barbell horizontal position beyond the toes. The latter was corrected through feedback.

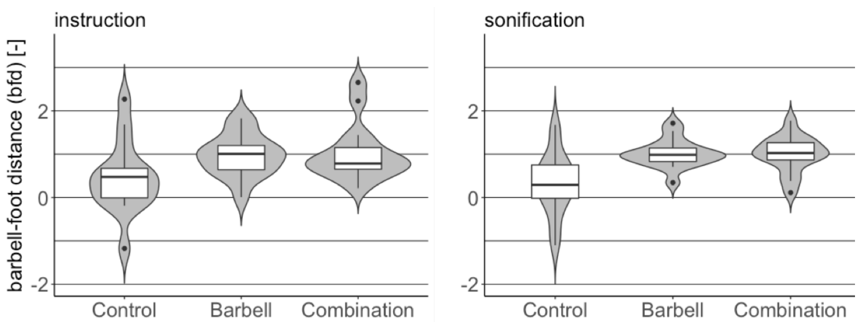

Figure 5.4: Non-dimensional barbell-foot distance distributions for points of performance spine *and* combination *and control condition. Instruction group (left plot) and sonification group (right plot)*

Comparisons of barbell-foot distance for points of performance *barbell* and *combination* with the control condition yield significant differences for both instruction and sonification feedback. In this case, no significant difference with respect to control is observed for point of performance *spine* as no feedback on

	instruction		control		test statistics	p
	mean	sd	mean	sd		
spine	-0.022 (Mdn)	–	0.021	0.253	z = -0.580	0.0001
barbell	0.069	0.441			t = 0.541	0.597
combination	-0.009	0.262			t = -4.306	0.0007

	sonification		control		test statistics	p
	mean	sd	mean	sd		
spine	-0.089	0.18	0.017	0.187	t = -2.651	0.018
barbell	-0.013	0.191			t = -1.451	0.167
combination	-0.106	0.211			t = -3.275	0.005

Table 5.1: Distributions of non-dimensional spine bend for all points of performance and control. For the normally distributed variables, means, standard deviations, t-values, and significance p are reported. Medians, z-values and significance p values for the non-normally distributed ones.

	instruction		control		test statistics	p
	mean	sd	mean	sd		
spine	0.54	0.827	0.455	0.824	t = 0.972	0.346
barbell	0.973	0.482			t = 3.546	0.003
combination	1.028	0.656			t = 3.044	0.008

	sonification		control		test statistics	p
	mean	sd	mean	sd		
spine	0.47	0.687	0.329	0.72	t = 1.920	0.073
barbell	1.014	0.324			t = 3.802	0.002
combination	1.027 (Mdn)				z = -3.522	0.0004

Table 5.2: Distributions of non-dimensional barbell-foot distance for all points of performance and control. For the normally distributed variables, means, standard deviations, t-values, and significance p are reported. Medians, z-values and significance p values for the non-normally distributed ones.

barbell-foot distance was provided in the session for this point of performance.

5.3.2 Difference between feedback types

In order to compare performances between the feedback types, movement improvements were considered. These were calculated as the differences of the mean measured output before (control condition) and after the feedback, for the two groups (instruction and sonification) separately. Only the point of performance *combination* is considered, as that is representative of the total final movement improvement. The same analysis was performed for the spine bend (sb) and barbell-foot distance (bfd), separately.

Spine bend differences. A preliminary analysis of normality of the data using Shapiro-Wilk test showed that the means of non-dimensional spine bend *sb* feedback - control was normally distributed for both feedback types: instruction p = .091 and sonification p = .068 and for the controls of both groups, control (sonification) p = .752 control (instruction), p = .690 control (sonification). Therefore parametric tests were used for the comparisons. The results of the comparisons are shown in Table 5.3. From the first row of Table 5.3 it can be observed that

spine bend (sb)		**test statistics**	**p**
control (instruction)	control (sonification)	t = -0.037	0.971
instruction	control (instruction)	t = -4.306	0.0007*
sonification	control (sonification)	t = -3.275	0.005*
instruction	sonification	t = -0.226	0.822

Table 5.3: Comparisons of non-dimensional spine bend for point of performance Combination *of both feedback (*instruction *and* sonification*) with respect to the control condition and between each other*

there is no significant difference between the two groups in the control phase. This confirms that initial movement parameters between the groups are statistically equivalent. Comparison of the spine bending between the control condition and the feedback reveals significant differences (p = .0007 and p = .005 for the instruction and sonification feedback respectively), indicating that both feedback types are effective in modifying spine bending. Quantitative comparison of the two feedback types is provided in Table 5.5. No significant differences could be observed in average spine bend performances between the two feedback types (row 4 of Table 5.3 , p = .82), nor for the difference in movement improvements (i.e. feedback-control) by the two feedback.

Distribution of spine bend for point of performance *combination* for the two feedback types and control are shown in the violin plots of Fig. 5.5

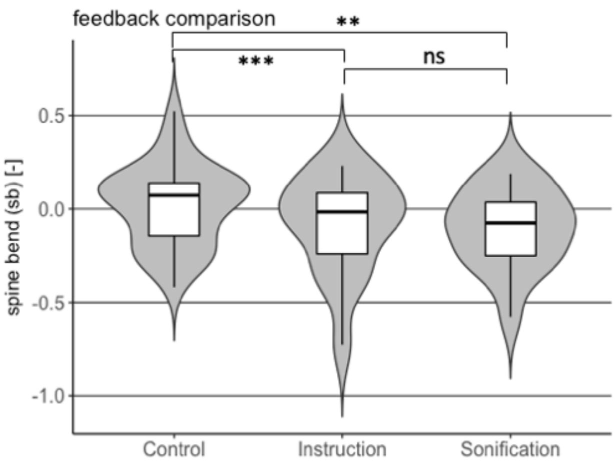

Figure 5.5: Comparison of spine bend distribution between instruction and sonification feedback with respect to control for point of performance Combination.

Barbell-foot distance differences. Tests of normality for the barbell-foot distance improvements (*bfd* feedback - control) by Shapiro-Wilk revealed that the differences between control of both groups are normally distributed, p = .398 for instruction and p = .153 for sonification group respectively. The movement improvement for the instruction group is also normally distributed (p = 0.316) while for the sonification group the barbell foot improvement is not normally distributed (p = 0.037). Parametric t-tests were used for the normally distributed differences while Wilcoxon Rank Sum tests for the non-normally distributed pairs. Results of the comparisons are shown in Table 5.4.

Distribution of barbell-foot distance for point of performance *combination* for the two feedback types and control are shown in the violin plots of Fig. 5.6

The main result of the presented analysis is that for both feedback types there is a significant movement improvement.

Improvements comparison From Table 5.5 is can be observed that the movement improvements with respect to control do not significantly differ for the two feedback types neither for spine bend (p = .721) nor for the barbell-foot distance (p = .922) This result seems to demonstrate that both feedback types are statistically non-significantly different from each other to achieve movement improvement. In particular, for the spine bend instruction feedback produces a mean improvement

barbell-foot distance (bfd)		test statistics	p
control (instruction)	control (sonification)	t = -0.451	0.654
instruction	control (instruction)	t = 3.044	0.009*
sonification	control (sonification)	z = -3.522	0.0004*
instruction	sonification	z = -0.683	0.805

Table 5.4: Comparisons of non-dimensional barbell-foot distance for point of performance Combination *of both feedback types (*instruction *and* sonification*) with respect to the control condition and between each other*

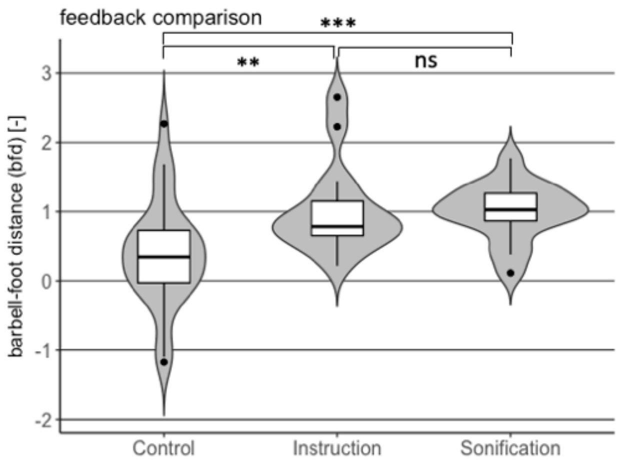

Figure 5.6: Comparison of barbell-foot distance distribution between instruction and sonification feedback with respect to control for point of performance Combination*.*

	movement improvement		comparison	
	instruction - control	**sonification - control**	**test statistics**	***p***
	mean (sd)	mean (sd)		
spine bend	-0.108 (0.096)	-0.124 (0.152)	t = -0.362	0.721
barbell-foot distance	0.573 (0.729)	0.755 (Mdn)	z = -0.097	0.922

Table 5.5: Comparisons of movement improvements between feedback types (instruction and sonification) for point of performance Combination. *Non-dimensional spine bend improvement and non-dimensional barbell-foot distance on first and second row respectively. Means, standard deviation and t-values are reported for normally distributed quantities, medians and z-values for non-normally distributed ones.*

of -0.108 while sonification -0.124. For the barbell-foot distance the instruction feedback produces a mean increase of 0.573 while sonification a median increase of 0.755.

5.3.3 Effect of expertise

Tests were performed to check if the level of expertise of the participants had an influence on the movement improvements with feedback. Linear models were constructed using movement improvement as independent variable and two fixed effects, namely feedback type and level of expertise. Four versions of this model were considered, varying the set of predictors : the null model (model 0, without feedback type and expertise), the full model (model FULL including predictors: feedback type and expertise), and two intermediate models (model FB with only feedback and model EXP with only expertise). The models were compared by means of anova using the standard anova function implemented in R. The same models were constructed considering movement improvements of spine bend and barbell-foot distance respectively. Results of the comparisons for spine bending models revealed that nor feedback type nor level of expertise have an effect in movement improvement. Comparison of model 0 with models FULL, FB and EXP yielded non-significant differences, respectively p = .635 , .723 and .431. Comparisons for the barbell-foot distance variable produced in the following results anova model 0 with model FBD, p = .701, model 0 with model EXP p = .025* and model 0 with model FULL p = 0.065. From the last results, it can be seen that experience is indeed a predictor of movement improvements while no conclusions can be drawn about feedback type. The predictions of model EXP for barbell-foot distance improvements are 1.29 for group A, 0.376 for group B and 0.67 for group

C. These results indicate that beginners of group A are the ones featuring largest improvement for barbell verticality. Surprisingly, the intermediate participants of group B featured less improvement compared to the experts group C.

Questionnaires information

After each set of repetitions, participants were requested to fill in a questionnaire describing the perceived feedback. The asked questions concerned the following characteristics, in order: Perceived Effort, Clarity of feedback, Pleasantness, Motivation, Accuracy, Match between performed movement and perceived feedback and Usability of the system. Answers were provided on a 7-point Likert scale from 1 to 7. Participants could further indicate if they received no feedback at all by inserting 0. The questionnaires information relative to two participants of the instruction group could not be used and were disregarded in the analysis. For the instruction group, 13 trials relative to a total of 8 participants received no feedback. The trials included all different points of performance (5 for *spine*,4 for *barbell* and 4 for *combination*). This indicates that movement was correct according to the trainer and no feedback was provided. For the sonification group, only 4 trials received no feedback, all relative to point of performance *spine*. Screenshots of all questionnaires can also be found at: https://doi.org/10.5281/zenodo.3355107.

Differences between feedback types Comparison of ratings of the two different feedback types was performed using Mann Whitney U tests. No significant differences were found between the two feedback types for the following characteristics: Perceived Effort p = .216, Clarity of feedback p = .634, Pleasantness .p = .729, Motivation p = .853 , Accuracy p = .838, Match between performed movement and perceived feedback p = .253 and Usability p = .224). This indicates that the proposed sonification feedback is performing analogously to standard instruction in terms of the above mentioned characteristic.

Correlation of the improvement with feedback ratings was performed using Kendall's tau-b correlation test. No correlation was found between the movement improvement and the asked characteristics of the feedback. This indicates that, in the present case, a better perception of the feedback did not directly translate into movement improvement. Within the same feedback group, no significant differences in terms of feedback characteristics were found across the different points of performance. Music background of the participant within the sonification group did not play a significant role in terms of movement improvement. Comparison by Mann Whitney U tests of the participants with music education (6) compared to the ones without (10) within the sonification group, yielded p = .382 for the spine bending and p = .635 for the barbell-foot distance. The latter results suggest that music education did not play a role in terms of movement improvement neither for the spine bending nor for the barbell-foot distance.

5.4 Discussion

In this study, we assumed that correct functional movements for weight lifting can be learned with the help of a music-based biofeedback system. We focused on one specific movement called deadlift, and we compared musical feedback with verbal feedback from experienced trainers. Our hypothesis was (i) that musical feedback has an effect on measured movements of the deadlift similar to verbal feedback, and (ii), that the musical feedback would be more motivating than the verbal feedback. The rationale was that music works as a natural reward, and therefore, that its sound quality can be used as a stimulus for reinforcement learning.

The test of the first hypothesis was based on an independent group analysis of measured parameters of the deadlift movement, namely spine bend and barbell-foot distance, before and after receiving feedback. No significant differences in performances were found. This confirms the first hypothesis, suggesting that the response of a weight lifter, either to a music-based biofeedback system or to a trainer's verbal instructions, are similar. This result opens for the possibility of using music-based biofeedback systems in the field of weightlifting. Apart from learning the technique, the system could be used by advanced athletes to further improve their technique by discovering minor aspects of their movement that are not fully visible by eye. In using the music-based biofeedback system, several participants reported discovering details about their movements they were not aware of.

The test of the second hypothesis was based on a questionnaire. Although the musical feedback scored high regarding clarity and pleasantness, no significant difference in results could be observed when compared against the instructions from the human trainer. This can be ascribed to the fact that most athletes are more accustomed to human feedback while performing sports. In addition, it should be mentioned that the feedback strategy was based on alterations of one basic music soundtrack chosen by the researchers rather than by the weightlifters themselves. Familiarity with the music, as well as the possibility of choosing one's own music, may have been a determining factor.

In this study, music was used as a regulator of reward. We thereby focused more on modifying the sound quality of a given music, rather than choosing the optimal preferred or familiar music. We reasoned that good sound quality of the music could work as reward and that bad sound quality of the same music could work as punishment. Through sonification, i.e. the translation of movement into sound quality, it then becomes possible to influence the functional movements of the weight lifter. Good movements are thereby translated into good sound quality, while bad movements are translated into bad sound quality. Given the fact that music is a natural reward, then it follows that good versus bad sound quality can steer actions towards obtaining the reward. More specifically, reinforcement can steer functional movements of the deadlift towards the intended correct and safe movements. Movements driven by musical feedback tend to be more correct than movements that are not driven by musical feedback (the control condition). The effect of musical feedback is similar to the effect of verbal feedback. Results thus showed that the proposed feedback system is able to improve the movement technique compared to the control condition and that there is no difference between the verbal and sonification feedback. Applications of reinforcement learning has proven to be effective in other sports applications (see Lorenzoni et al., 2018) as long as the subjects are able to modify their behavior and achieve reward. In contrary, a negative reinforcement was observed when participants were not able to achieve the target behavior. This could be partly explained by fact that the use of such a technological system is relatively new and would need time for athletes to get acquainted with. It seems that participants receiving the musical feedback were more focused on minimising music alterations, than on the motivating value of the music itself. In future experiments, different signification strategies could be compared as feedback, and the effect of different background music tracks could also be investigated.

A positive correlation was found between level of improvement and experience level of the participant for the barbell-foot distance, irrespective of the feedback kind. In particular, the least experienced participants featured the highest improvement. Surprisingly, the intermediate participant group featured lower movement improvements with respect to the expert group. This could be explained by the fact that experts are experimenting more with the system compared to intermediate experienced participants. However, larger group with similar expertise levels would be required to draw strong conclusions on this aspect.

In the present experiment, feedback of the spine curvature was only provided for positive spine curvature, i.e. flexion (forward bending), and no feedback was provided for extension (backward bending). The reason for this was two-fold. The first was that this is typically the main fault in deadlift, and where the majority of injuries arise; it comes from excessive flexion of the spine as the athlete progresses through the movement. This can arise from an improper starting position, which impacts the rest of the movement, or a loss of neutral spine (i.e. flexion) during the progression of the movement due to the force of the external load. The second reason was that providing feedback also on extension was deemed to be excessive and to overload the participants with too much information that would not be actionable in correcting the main concern - flexion of the spine under load.

The same barbell (20kg) and weights (two 5 kg plates) for a combined weight of 30kg were used for the experiment for all participants. No effect of fatigue was reported by any of the participants, which all reported to regularly perform sport activities.

Previous works by Murgia et al. (2012) and Fritz et al. (2013) have focused on the increase in power output and arousal deriving from sonification of movements in weightlifting. The focus of the present work was more oriented towards improvement of technique for injury prevention, and power output was not directly measured. The authors believe that the empowerment deriving from music-to-movement alignment might lead to alterations of movement patterns and particular attention should be paid to pure sonification of movements in sports that require specific technique for minimizing the risk of injuries. Future tests might be dedicated to investigating the effect of the presented system on power output.

Each biofeedback method appeared to result in moderate to large effects immediately during application. However, it is unknown whether the effects were maintained after the experimental session (i.e. in future workout sessions). Future studies should ensure adequate balancing of participants and include retention testing to assess the long-term success of the proposed biofeedback method.

The present approach is tailored to the single participant in terms of correct and dangerous positions. Alternative procedure for automatic classification of movements correctness is currently being developed; this is based on machine learning algorithms applied to movement acquisitions on a large panel of individuals. Such procedure would generalize the movement parameters and minimize inter-subject variability when acquiring the initial parameters.

5.5 Conclusions

A music-based biofeedback system was developed that is able to provide auditory feedback when performing deadlift movements. The system is based on sonification, that is, on the translation of movement parameters into the sound quality fo a musical track. This translation has an appeal to the human reward system such that music-based reinforcement learning becomes possible. The system was compared to standard verbal instructions by an instructor. Both feedback types were able to improve the movement parameters with respect to an initial condition and were perceived equivalently clear and pleasurable by participants. The current findings suggest that such systems are a valuable addition to current training methods and more motivational versions could be developed to be used also in the fields of rehabilitation and medical treatments. Further advances of the system could be improved portability by using wearable sensors for back posture detection. The proposed audio modifications could be easily implemented on portable music players and headphones. This would allow the system to be used in more ecological settings and by multiple athletes simultaneously. Furthermore, the proposed feedback approach could be extended to other functional movements to address similar challenges for improving technique and safety.

My main contribution is: help in development of the system, analysis of the data, and writing part of the paper.

6
The SoundBike

Pieter-Jan Maes, Valerio Lorenzoni and Joren Six

In *Journal on Multimodal User Interfaces*, 2017

Abstract

The spontaneous tendency of people to synchronize their movements to music is a powerful mechanism useful for the development of strategies for tempo adaptation of simple repetitive movements. In the current article, we contribute to such strategies – applied to cycling – by introducing a new strategy based on the sonification of cyclists' motor rhythm. For that purpose, we developed the SoundBike, a stationary bike equipped with sensors that allows interactive sonification of cyclists' motor rhythm using two distinct but compatible sonification methods. One is based on the principle of step sequencers, which are frequently used for electronic music production. The other is based on the Kuramoto model, allowing automatic and continuous phase alignment of beat-annotated music pieces to cyclists' motor rhythm, i.e. pedal cadence. Apart from an in-depth presentation of the technical aspects of the SoundBike, we present an experimental study in which we investigated whether the SoundBike could enhance spontaneous synchronization of cyclists to external music. The results of this experiment suggest

that sonification of cyclists' motor rhythm may increase their tendency to synchronize to external music, and helps to keep a more stable pedal cadence, compared to the condition of having external music only (without sonification). Although the results are preliminary and should be followed-up by additional experiments to become more conclusive, SoundBike seems anyhow a promising interactive sonification device to assist motor learning and adaptation in the field of sports and motor rehabilitation.

6.1 Introduction

In the domain of sports and motor rehabilitation, sonification of physical and physiological data is typically used to serve three functions, namely to motivate, to monitor, and/or to modify human performance (for an in-depth discussion, see Maes et al., 2016).

Auditory feedback has been proven particularly useful in assisting motor learning and adaptation. The way sonification, or auditory biofeedback, is deployed for this purpose may rely on different strategies. The most typical strategy pertains to a goal-driven approach. This approach requires that the learner has an explicit representation of the target behavior, i.e. the goal. Sonification then functions as mere information carrier, allowing people to monitor their behavior, compare it to the target behavior, and adapt their behavior if required (Dubus and Bresin, 2013; Sigrist et al., 2013; Bevilacqua et al., 2016). As indicated by Leake and Ram (1995), this process is guided by reasoning and attention mechanisms and may therefore not always be the most appropriate strategy. Recently, a promising alternative strategy is being explored, drawing upon basic principles from the reinforcement learning paradigm. Reinforcement learning is rooted in the idea that people act and behave so as to maximize outcome reward. Hence, when coupling a reward to a desired behavior, people are likely to exhibit this behavior spontaneously, without needing to be told explicitly what to do. In this context, music and sound are particularly relevant as they might be rich sources of reward and pleasure (Maes et al., 2016). One important source of pleasure in our interaction with music is entrainment or synchronization (Huron, 2006; Phillips-Silver et al., 2010; Leman, 2016). Thanks to this pleasure, people often exhibit a spontaneous tendency to align their movements to perceived patterns in the music, such as the beat. Spontaneous synchronization is a phenomenon ubiquitous in behavior of biological systems, ranging from the simultaneous flashing of fireflies to a collection of neurons firing (Strogatz, 2003). Likewise, human behavior often synchronizes unintentionally to external periodic stimuli in the environment, to which it is perceptually (and meaningfully) coupled. The most typically studied behavior is how movements of two or more individuals become synchronized in rhythmical activities, such as walking, sprinting, rhythmic arm or finger movements, rocking in chairs, or swinging pendulums (see Repp and Su, 2013, for an estended review). Music is a periodic stimulus *par excellence* that stimulates human auditory and interpersonal motor synchronization (Phillips-Silver et al., 2010; Clayton, 2012; Keller et al., 2014). The musical beat, constituting the musical tempo (cf. beats per minute), thereby functions as most elementary periodic structure to which movements are aligned. The specifics of synchronized movement behavior to music is dependent on a multitude of factors, including the characteristics of the musical material, personal factors, and the environment in which the musical activity is situated (cf. Repp and Su, 2013). However, what is of importance here, is the mere principle that a lot of humans have an impelling drive to adapt their movements in order to get them aligned to the temporal acoustic energy profiles constituting music.

Earlier studies have exploited this principle into music and sonification strategies for tempo adaptation of simple repetitive movements, such as in tapping or running (Maes et al., 2015; Van Dyck et al., 2015; Buhmann et al., 2017; Moens and Leman, 2015; Moens et al., 2014). Maes et al. (2015) conducted an experiment, in which participants had to tap series of regular (target) intervals (i.e. synchronization-continuation paradigm). At each tap, participants received a piano tone as auditory feedback, of which the duration in specific conditions matched exactly the duration of the target interval. Interestingly, it was found that when gradually shortening the tones' duration throughout the continuation phase of a trial, participants spontaneously increased their tapping tempo (that is, shortened the produced temporal intervals). This finding was explained based on an auditory-motor coupling and error-correction mechanism; accordingly, auditory feedback (the ending of a tone) functioned as reference for the timing behavior (the onset of the next tone). In another series of studies (Van Dyck et al., 2015; Buhmann et al., 2017; Moens and Leman, 2015; Moens et al., 2014), sonification strategies were developed for spontaneous adaptation of running tempo. These studies are based on the D-Jogger application that enables to automatically phase-align music (i.e. the beat) to a runner's cadence (i.e. the footfall) (for more info on the D-Jogger, we refer to Moens and Leman, 2015; Moens et al., 2014). In one study, by Buhmann et al. (2017), it was found that shifting the musical beat in reference to a runners' footfall may influence their cadence, speed, and enjoyment. Concretely, when placing the beat slightly before the footfall, runners have the tendency to increase running cadence and speed. In contrast, when beats are placed slightly after the footfall, running cadence is decreased. Again, the explanation is given in terms of people's drive to align movement patterns to (learned) patterns in the music (cf. auditory-motor and error-correction mechanisms). In the current study, we want to specifically elaborate on the strategy introduced in Van Dyck et al. (2015) to realize tempo adaptations in runners' comfort tempo. In this study, runners were first presented music that was automatically phase-aligned with their steps, using the D-Jogger sonification system. After, music was gradually sped up or slowed down, and they hypothesized that runners would unconsciously speed up or slow down their running pace accordingly, to continue the pleasant experience of being entrained with the music. In general, this hypothesis was confirmed as a linear relationship was found between musical tempo manipulations and runners' cadence tempo adaptation. However, there seemed to be a substantial group of runners that were not (or much less) influenced by the musical tempo manipulations.

The goal of the current article is to elaborate on this strategy in an attempt to make it more effective and useful for movement tempo manipulation purposes (applicable in the domain of sports, motor rehabilitation, and active living). The central question of this article is how we can increase people's tendency to spontaneously synchronize a rhythmical movement activity to an external musical stimulus. The core of the solution that we put forth, is based on the addition of a sonification of people's motor rhythm. By transferring their motor pattern into audible form, we hypothesize that people will more likely spontaneously synchronize to an external musical rhythm, as both are then presented in the same (auditory) modality. An important consequence of this approach is that people have an active contribution to the musical outcome, which may have an empowering effect (Leman, 2016; Fritz et al., 2013). We hypothesized that people would be motivated, without being instructed, to synchronize to an external musical stimulus as this leads to a pleasant sounding (i.e. rewarding) coherent musical whole, in contrast to when they are not in sync. In the current article, we wanted to empirically test this new sonification strategy in the context of cycling.

In recent research, studies have been conducted that explored the potential of real-time auditory feedback for motivating, monitoring, or modifying cycling performance. A previous study (Maculewicz et al., 2013) explored how auditory feedback of cyclists' (N=8) pedal frequency – in terms of periodic drum sounds – could improve cyclists' ability to follow the tempo of an external rhythmic drum pattern. The results indicated that the chosen type of auditory feedback was rather disturbing for cyclists' performance. Interestingly however, the authors put forth suggestions for follow up studies, including the suggestion of exploring continuous feedback and other musical material, such as melodies. In another study, it was investigated how real-time sonification of the pedaling speed rate – in terms of everyday sound effects such as chassis and chain sound – could influence cyclists' (N=21) perception of effort and of mechanical resistance (Bruun-Pedersen et al., 2017). The results yielded an effect on perceived mechanical resistance, but not on perceived effort. In another study, Schaffert et al. (2017) explored a strategy to audibly represent different pedaling shapes (i.e. force-time profiles) as real-time fluctuations in tone pitch. Results show that this parameter-mapping sonification was intuitively understandable (N=24), and practically effective in monitoring – and potentially improving – pedal stroke characteristics (N=4). Finally, in a study by Sigrist et al. (2016), it was examined to what extent auditory feedback – in terms of mapping the crank moment to the frequency of a violin sound – could assist cyclists (N=6) in learning a specific bipedal pushing-pulling pattern. Unfortunately, the sonification was not very motivating and hardly effective in modifying cyclists' pedaling performance.

The results of these studies – although preliminary – indicate that further work is required to exploit the full potential of real-time sonification for motivating, monitoring, and modifying cycling performance. In the current article, we further explore the sonification strategies discussed above based on synchronization mechanisms and reinforcement learning for pedal frequency regulation and adaptation. For that purpose, we first had to design a technological solution that allowed to sonify the motor rhythm – i.e. pedal cadence and pedal pressure – of cyclists. In this article, we present such a solution, in the form of a bike for interactive sonification, called the SoundBike (Section 6.2). We provide an in-depth description of the hardware components of the SoundBike in Section 6.2.1, as well as of the two different methods that were implemented to allow the sonification of cyclists' motor rhythm (Section 6.2.2). After, we present an empirical study in which we actually tested how the SoundBike can be used to increase people's tendency to synchronize to an external musical stimulus (Section 6.3).

6.2 SoundBike – a bike for the sonification of a cyclist's motor rhythm

6.2.1 Hardware

The SoundBike is a stationary bike equipped with sensors that allows the sonification of a cyclist's motor rhythm, i.e. pedal cadence.This sonification was based on two performance parameters, namely circular crank position and pedal pressure. Circular crank position was measured using an optical rotary encoder mounted to the crank axis. We used a HEDS-6140 encoder wheel – customized to fit the crank axis – and a HEDS-9040 optical reader by Avago Technologies. Using this rotary encoder, we obtained a real-time and continuous indication of the circular crank position, expressed as an angle ranging from 0° to 360°, with an accuracy of 1.44° (as one rotation was defined by 250 discrete measurement points). To measure pedal pressure, we custom-made a pedal that consisted of two thin, but rigid, metal plates of dimensions 8-by-9 cm. In between these plates, matched load cell technology sensors were fixed at the four corners. On the top plate, we mounted a Shimano pedaling dynamics (SPD) clip system to ensure fixed foot positions. As a measure for pedal pressure, we took the average pressure detected across all four load cells. For the purpose of the experiment, it was sufficient to identify the circular position where cyclists applied maximal pedal pressure throughout a complete rotation.

The analog-to-digital conversion of the sensor signals (i.e. circular crank position and pedal pressure) was done using a Teensy 3.1 microcontroller mounted to the bike, and signals were send to a MacBook Pro laptop (2.2 GHz Intel Core i7; 16 GB 1600 MHz DDR3; OS X El Capitan) through a universal serial bus (USB) connection. For the sonification of the signals, we used the software Max/MSP 6 from Cycling '74.

6.2.2 Sonification methods

The SoundBike facilitates the sonification of the motor rhythm based on two distinct methods, described into more detail in the following two sections.

6.2.2.1 Method 1: Mapping audio samples to angular positions – a circular step sequencer approach

The first method is based on the principle of step sequencers, which are frequently used for electronic music production. Step sequencers allow to create and playback rhythmic and melodic patterns, using a visual grid format (see Figure 6.1, left). The vertical dimension of the grid consists of separate tracks each defining a particular sound event (i.e. an audio sample or synth instrument sound). The horizontal dimension of the grid presents a time line consisting of discrete steps that can be selected to trigger sound events at particular moments through time. The time line is organized into bars, beats and further subdivisions of that beat, typically leading to 8, 16, 32, or 64 step patterns. Individual patterns can be looped, or combined with other patterns at a user-defined tempo (e.g. in beats per minute, BPM).

In the context of the SoundBike, we applied this idea to allow sonification of cyclists' motor rhythm. The most important change however, is that we take the time line as a circular path, rather than as a horizontal line (see Figure 6.1, right). Steps can then be defined as angular positions of the pedal crank (in radians), and tempo as the rotation rate of the pedal crank expressed as the angular frequency (ω, in radians per second). Practically, sound events (audio samples or synth instrument sounds) can be mapped to specific angular positions of the crank's rotation and be triggered when the bike's crank passes by these positions. Hence, rhythmical and melodic patterns can be created that encompass one or more pedal crank rotations. In principle, one complete crank rotation can contain 250 discrete steps. In practice, however, one uses only a fraction of all these possibilities (e.g. see Section 6.2.1).

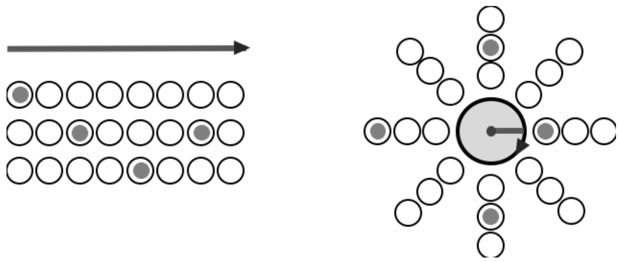

Figure 6.1: Left: visual representation of a "traditional" step sequencer. Right: visual representation of the circular format employed by the SoundBike.

6.2.2.2 Method 2: Automatic and continuous phase-alignment of music to the motor rhythm

Both cycling and (most) music are phenomena that exhibit periodically repeating (oscillatory) patterns. When cycling, the pedal crank makes a perfect circular rotation around its axis. Accordingly, angular motion of the pedal crank can be represented as a phasor rotating in a unit circle. In (most) music, the most obvious periodic pattern is the perceived beat pattern, also referred to as musical pulse or tactus. It is a pattern that consists of discrete beats, which are temporally located at equal time intervals. Accordingly, this temporal pattern may be represented as a phasor rotating in a unit circle as well, and the duration of one single temporal interval then becomes represented by one complete rotation (= $2\pi\ rad$) of the phasor.

The idea underlying the second sonification principle is to provide a method that allows to automatically and continuously align the phasor of the music to the phasor of the pedal rotation. Consequently, this would allow to adapt the playback of the music in a way that the musical beat aligns with a specific angular position of the pedal, preferably the position where pedal pressure is at its highest value throughout a rotation (see further; P_{max} index). For this purpose, we propose a method based on the Kuramoto model (Kuramoto, 1975).

An oscillator has a natural frequency ω and an instantaneous phase θ. A system of oscillators has a phase coherence factor. The phase coherence determines how similar the phase for each oscillator is in the system. If all oscillators are synchronized – the frequencies and phases are equal – then the phase-coherence equals one. For a system of random oscillators, the phase coherence is expected to be close to zero. If oscillators are coupled, then one oscillator affects all others. In an uncoupled system, the oscillators do not interact.

The Kuramoto model describes a way to maximize phase coherence in a system of coupled oscillators. To be able to get to, and maintain, a close phase relationship, the natural frequencies of each oscillator in the system should be relatively close to each other. The Kuramoto model adapts the phase – and consequently the frequency – of each oscillator incrementally to come closer together (to entrain). The strength of the coupling is determined by a coupling factor K . The following equation determines how to adapt oscillator i , for Noscillators:

$$\frac{d\theta_i}{\mathrm{dt}} = \omega_i + \frac{K}{N}\sum_{j=1}^{N}\sin\left(\theta_j - \theta_i\right)\ i = 1 \ldots N \tag{6.1}$$

In our system, there are only two oscillators. The first oscillator is the music. We use musical pieces encoded in typical audio formats, such as .aiff, .wav, .mp3, etc. The BPM of that music then determines the natural frequency ω_m, and the time within an inter-beat interval determines the phase θ_m. To correctly calculate θ_m, it is required for our system to have an indication of the time points where beats occur in a musical piece. The second oscillator is the rotating pedal crank. The pedals are operated by a user so ω_p is equal to the pedal cadence, expressed as rounds per minute, RPM. The phase θ_p is determined by the angular position of the pedal crank relative to the point of maximum pedal pressure (see further P_{max} index). This reference is also shared with the music oscillator, meaning that the first beat sounds when the pedal crank passes the angular position corresponding to P_{max} index.

In this system of two oscillators, the playback of the music (oscillator 1) is adapted via the pedal cadence (oscillator 2) of a cyclist. A technique to adapt playback speed without modifying pitch called time-stretching is used here. Both oscillators can be considered to be coupled since the subject almost always has a tendency to synchronize with music and in turn the music adapts to changes in pedal cadence. In terms of the Kuramoto model, $\theta_m - \theta_p$ (the relative phase) needs to be minimized continuously and the first equation is simplified to:

$$\frac{d\theta_m}{dt} = \omega_m + \frac{K}{2}\sin\left(\theta_m - \theta_p\right) \tag{6.2}$$

We implemented the Kuramoto model in a Max/MSP 6 patch (see Figure 6.2). For audio time-stretching, we used the elastic~ object, which employs the commercial zplane lastique algorithm. Private communication with Alexander Lerch, the developer of the algorithm, suggests that a phase vocoder with transient detection (harmonic/percussive separation) is used with the addition of many special cases added to ensure that results are satisfactory for almost all musical signals (for a review of various algorithms to modify time scale of musical signals, see Driedger and Müller (2016)).

The elastic~ object provides a qualitative solution that doesn't create much audible artifacts when time-stretching or when changing time-stretching factors in real-time. The coupling strength K is determined experimentally: A *hard* coupling changes the music abruptly, a *soft* coupling never reaches phase coherence. In

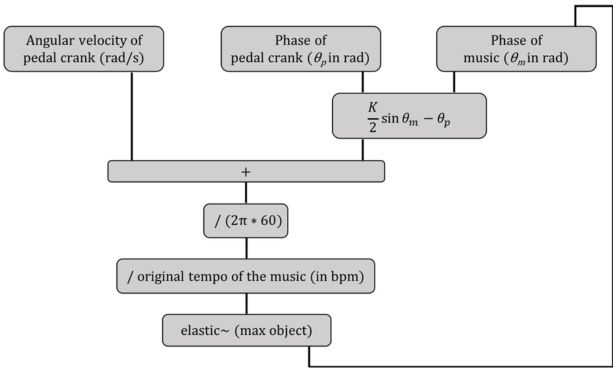

Figure 6.2: Schematic representation of the Max/MSP patch that realizes automatic and continuous phase-alignment of music to the motor rhythm of the cyclist, based on the Kuramoto model

practice, cyclists, can maintain a relatively stable pedaling frequency p so this parameter has some leeway.

6.3 Experiment

In the following, we present the experiment in which we tested whether the Sound-Bike allows to enhance cyclists' tendency to spontaneously synchronize to external music, based on applied sonification strategies.

6.3.1 Method

6.3.1.1 Participants

Fifteen participants (7 females, 8 males, mean age = 32.5 years, age range = 18-45 years) took part in the study. All participants signed a consent form indicating that they participated on a voluntary basis and received no compensation in return for their participation. Concerning their cycling background, 8 participants cycled daily, 4 several times a week, 1 more than once a month, and 2 less than once a month. Concerning their musical background, 7 participants had not received formal music education, 5 played music on an amateur level, and 2 had received formal music education.

6.3.1.2 Stimulus

For the experiment, we created a short musical stimulus that was composed of a beep pattern, drum pattern, and melody pattern (see Figure 6.3). The playback of each pattern could be coupled to the pedal crank rotation of a cyclist, using either one of both sonification methods explained in Section 6.2.2. The beep pattern contained one beep sound per pedal crank rotation. The beep sound was a short pure tone, with a pitch frequency of 400Hz, and a tone duration of 50ms. Importantly, the onset of the beep was aligned to the angular position of the pedal crank at the time that the left foot applied its highest pressure throughout a rotation, i.e. the P_{max} index. The drum pattern consisted of a typical kick–hihat–snare–hihat sequence, evenly spread over one complete pedal crank rotation. Again, the onset of the pattern – i.e. the kick – was aligned to the time of highest pedal pressure, i.e. P_{max} index. Finally, the melody pattern contained a simple melody played by a bell-like sound. The melody was written in a 2/4 time signature, in a way that one complete pedal crank rotation corresponded to one musical bar, consisting of two beats (taken as quarter notes). Again, the first beat of each bar was aligned to P_{max} index. The complete melody pattern consisting of eight musical bars is thus mapped onto eight consecutive pedal crank rotations.

The audio playback of the external music and sonification was provided using a stereo setup comprising two Behringer B2031 A Truth active studio monitors at a predefined, comfortable volume, which was the same for all participants.

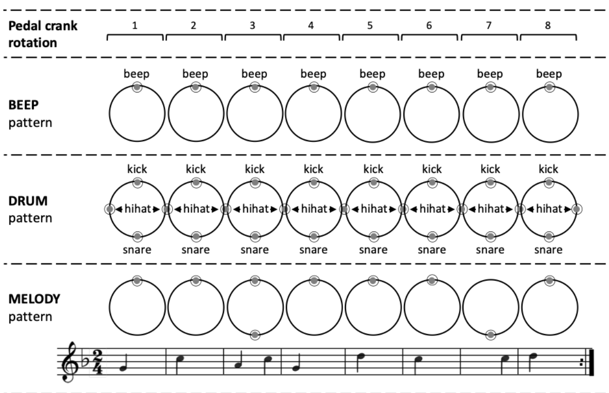

Figure 6.3: Visual representation of the overall musical pattern covering eight consecutive pedal crank rotations. The dots on the circles indicate angular positions within a rotation of the pedal crank to which audio samples are mapped. The different layers could be separated from each other and differently combined as external stimulus or sonification pattern (see Table 1).

of the overall musical pattern covering eight consecutive pedal crank rotations. The dots on the circles indicate angular positions within a rotation of the pedal crank to which audio samples are mapped. The different layers could be separated from each other and differently combined as external stimulus or sonification pattern (see Table 1).

6.3.1.3 Procedure and design

Participants came individually to the laboratory to participate in the experiment. They were each given a short explanation of the procedure and the tasks they had to carry out. They signed an informed consent and filled out a short pre-questionnaire, informing about their age, sex, musical background, and sports/cycling background. After, they received cycling shoes to put on, compatible with the SPD clip-in system. Then, before the actual experiment, they were given some time riding on the SoundBike (without sonification or music) in order to get used to the bike and to warm up their muscles. When they indicated to be ready, the actual experiment could start off.

The experiment consisted of a series of five trials – each 270s in duration – in which we tested the effect of different motor rhythm sonification patterns on cyclists' tendency to spontaneously synchronize to external music. A duration of 270s per trial was chosen in order that the total cycling duration of one participant throughout the complete experiment (warm-up + 5 conditions) would take about a half an hour. Accordingly, we tried to avoid that fatigue effects and the potential experience of boredom would have too much effect on the outcome of the experiment. Before each trial, participants were instructed to ride at a comfortable steady tempo, uninterrupted for the complete duration of the trial. Each trial followed a similar, four-part trial procedure, which is schematically represented in Figure 6.4 and explained into more detail in the following paragraph.

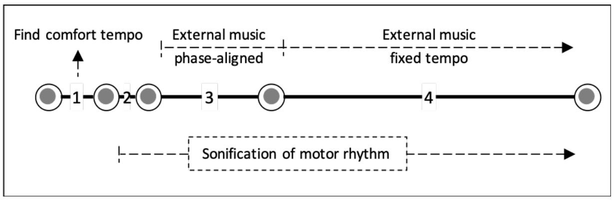

Figure 6.4: Schematic overview of the experimental trial procedure, consisting of four distinct parts, but performed uninterrupted

the experimental trial procedure, consisting of four distinct parts, but performed uninterrupted.

In the first part of a trial (duration = 20s), no sonification or external music was provided yet. This part was meant for participants to find their own comfort tempo. Also, the system detected the angular position at which a participant, on average, applied the highest pressure with the left foot throughout a pedal crank rotation. This angular position – termed P_{max} index – was chosen as the onset of the motor rhythm throughout the respective trial.

In the second part of a trial (duration = 10s), we added sonification of the cyclist's motor rhythm, employing the method explained in Section 6.2.2.1. The sonification patterns that were tested in the different experimental conditions (see next paragraph) were the beep pattern, melody pattern, and drum pattern, as discussed in Section 6.3.1.2 and shown in Figure 6.3. The onset(s) of these sonification patterns were respectively the beep, the first quarter note of each bar, and the kick. Until the end of the trial, a specific sonification pattern was played in a loop, with onsets aligned to the onsets of the motor rhythm (i.e. the P_{max} index of the consecutive pedal crank rotations).

In the third part of a trial (duration = 60s), external music was added, also played in looped repetitions until the end of the trial, on top of the sonification. In this part, we employed the audio time-stretching method explained in Section 6.2.2.2 so that the external music was continuously phase-aligned with the participant's motor rhythm and sonification pattern, so that a coherent musical whole was sounding.

In the fourth part of a trial (duration = 180s) the external music was decoupled from the participant's motor rhythm and played at a fixed tempo (that was, the tempo detected at the end of the third part), while the sonification pattern did remain aligned to the participant's motor rhythm.

All participants had to perform this trial procedure under five different sonification conditions (within-subjects design), in randomized order. The conditions differed according to the musical patterns that were used for sonification and external music. All musical patterns were based on the stimulus material presented in Section 6.3.1.2 (i.e. beep pattern, melody pattern, and drum pattern). An overview of the three experimental conditions (beep, melody, and drum) and two control conditions (no sonification and silence) is given in Table 6.1.

Sonification condition	**Sonification**	**External music**
Beep condition	Beep	Drum + Melody
Melody condition	Melody	Drum
Drum condition	Drum	Melody
No sonification condition	None	Drum + Melody
Silence condition	None	Silent

Table 6.1: Overview of the three experimental conditions, indicated above the dotted line (beep, melody, and drum) and two control conditions, indicated below the dotted line (no sonification and silence), which differed according to the musical material that was used for the sonification of the motor rhythm and the external music

experimental conditions, indicated above the dotted line (beep, melody, and drum) and two control conditions, indicated below the dotted line (no sonification and silence), which differed according to the musical material that was used for the sonification of the motor rhythm and the external music.

6.3.1.4 Analysis

The focus of the analysis was on the cyclists' performance in part 4 of each trial. In this part, the external music was presented at a constant tempo and we were interested in how the different sonification patterns had an impact on participants' tendency to synchronize with the external music (i.e. synchronization strength) and on their cadence tempo stability. For that purpose, we calculated two corresponding dependent variables based on the data collected in part 4 of each trial.

Synchronization strength. For each beat that occurred in the external music, we identified the corresponding angular position of the pedal crank. We plotted these positions as points (or vectors) on the circumference of a unit circle, leading to n points or unit vectors (with n depending on the cyclists' tempo). Using circular statistics, we then calculated an average vector from all n vectors, leading to a resultant vector R . The magnitude (i.e. length) of R is a measure for the consistency of the phase relationship between the external music and a cyclist's motor rhythm (i.e. pedal cadence), and was taken as measure of synchronization strength. For all participants, we calculated the magnitude of R in each condition (i.e. dependent variable 1), leading to a 15-by-5 matrix which could be further analysed for average differences across conditions using statistical methods (see further).

Tempo stability. In part 4 of a trial, we calculated all individual rotation durations, as the inter-onset intervals (IOI, in s) between the times that the pedal crank passed by the angular position identified as the P_{max} index (see above). This led to a distribution of n IOIs per trial. From that distribution, we removed IOIs that exceeded three times the standard deviation from the mean (that was 0.42% of all IOI data points). From the distribution of remaining IOIs, we calculated the coefficient of variation by taking the standard deviation, by dividing this by the mean, and subsequently multiplying the obtained value by 100. Measured as a percentage to the mean IOI, the coefficient of variation (CV%) is a tempo-independent measure that expresses how "spread out" IOIs are within a distribution. Hence, the lower the value, the more stable (consistent) a cyclist's tempo was throughout a trial. For all participants, we calculated CV% in each condition (i.e. dependent variable 2), leading again to a 15-by-5 matrix which could be further analysed for average differences across conditions using statistical methods.

6.3.1.5 Statistics

For our two dependent variables – magnitude of R (synchronization strength) and CV% (tempo consistency) – we obtained a 15-by-5 matrix of values (i.e. participants-by-conditions). If data were normally distributed (indicated by a Kolmogorov-Smirnov test), we used a one-way repeated measures analysis of variance (ANOVA) to test for differences between the averages of the different conditions (beep, melody, drum, no sonification, and silence). If the assumption of sphericity was not met (indicated by a Mauchly's test), we used Greenhouse-Geisser corrected p -values. In the case data were not normally distributed, we used a Friedman test to test for differences between the average ranks of the different conditions. All effects are reported at a general significance level (p -value) of .05. To follow up on statistical main effects, we performed post hoc analyses. These consisted in performing pairwise comparisons between conditions by applying a series of paired t -tests (in the case of normal data) or Wilcoxon signed-rank tests (in the case of non-normal data). To control for family-wise error rate, we used the Bonferroni method for correction of the significance level of post hoc tests. As we had 10 pairwise comparisons, effects of post hoc tests required a p-value below .005 (.05/10) in order to be significant at the general significance level of .05.

6.3.2 Results

In this section, we report all significant effects found according to the methods described in Section 6.3.1.5.

Synchronization strength (i.e. magnitude of resultant vector R). A one-way repeated measures ANOVA was conducted with sonification condition as within-subjects factor (beep, melody, drum, no sonification, and silence). The averages of all conditions are displayed in Figure 6.5. The results yielded, on average, a significant main effect of sonification condition on resultant vector length, F (2.73, 38.16)= 6.92, p = 0.001 (Greenhouse-Geisser corrected),η_p^2 = 0.33. A post-hoc analysis indicated a significant difference between the beep condition (M = .465, SEM = .077) and the silence (M = .146, SEM = .026), p < .05, t (14) = 4.04, g = 1.43 (= very large effect size). Also, a significant difference was found between the beep condition and melody condition (M = .295, SEM = .051), p < .01, t (14) = 4.12,g = 0.67 (= medium effect size). Finally, a marginal significant difference was found between the beep condition and the no sonification condition (M = .296, SEM = .053), p = .066 (uncorrected p= .007), t (14) = 3.19, g = 0.66 (= medium effect size).

Tempo stability (i.e. CV%). A Friedman test was conducted with sonification condition as within-subjects factor (beep, melody, drum, no sonification, and silence). The averages of all conditions are displayed in Figure 6.6. The results signaled a significant main effect of sonification mode, $\chi^2(4)$ = 14.99, p = .005. A posthoc analysis indicated that this main effect was due to a significant difference between the beep condition (Mdn = 1.827) and the no sonification condition (Mdn = 2.101), z = -3.124, p< .05, r = -0.5704 (= large effect size).

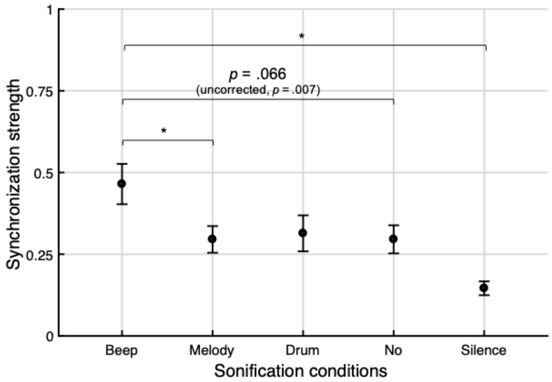

*Figure 6.5: Resultant vector length - as a measure of synchronization strength - averaged across all participants (N15) per sonification condition (beep, melody, drum, no sonification, and silence). Error bars represent standard errors of the mean *p < .05 (corrected for multiple comparisons, using Bonferroni method; .05/10*

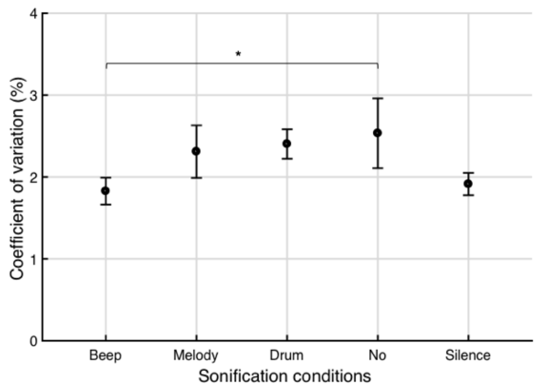

*Figure 6.6: Coefficient of variation (CV%) - as a measure of tempo stability - averaged across all participants (N15) per sonification condition (beep, melody, drum, no sonification, and silence). Error bars represent standard errors of the mean *p < .05 (corrected for multiple comparisons, using Bonferroni method; .05/10)*

6.3.3 Discussion

In the experiment, the main goal was to assess the influence of sonification patterns (beep pattern, melody pattern, and drum pattern) on cyclists' tendency to synchronize with external music, using the SoundBike. It was of our interest, to consider effects in relation to two control conditions, as well as in relation to the different sonification strategies.

A first control condition was the silence condition. In this condition, external music was present, but not audible to the participants as we turned off the volume. The reason for including this condition was – in the case of investigating synchronization strength – to obtain a general estimate of the degree of consistency in phase relationship that was established due to chance. Similarly, in the case of investigating tempo stability, this silence control condition allowed us to have a general estimate of participants' ability to keep a steady tempo without any music or sonification. Hence, by comparison with this silent control condition, we could assess actual effects of external music, whether or not in combination with sonification of the motor rhythm.

A second control condition was the no sonification condition. As the name implies, in this condition, we did not apply any sonification of the participants' motor rhythm and so participants could only passively listen to the external music, without having any active musical contribution. This is similar to the situation in the study of Van Dyck et al. (2015) on spontaneous entrainment of running cadence to the tempo of external music. By including this condition, we could asses the effects of added sonification of the cyclists' motor rhythm.

Next to comparison with these control conditions, we were interested in effects of different sonification patterns of the motor rhythm. Therefore, we included the three sonification patterns that either consisted of a beep pattern, melody pattern, or drum pattern. We consider results – both for synchronization and tempo stability in view of these three levels

Looking at synchronization strength, results demonstrated a significant increase in spontaneous synchronization compared to chance level (i.e. silence condition) for the beep condition only. However, in our overall interpretation of the obtained results, we should take into account the Bonferroni method, used to correct for multiple comparisons. This method is known to be extremely conservative, especially in our case of a relatively high number of conditions, inflating the rate of false negatives. Therefore, we believe that it is valuable to consider effects without corrected significance levels for multiple comparisons as well, in order to detect general tendencies that could be further explored in future research. In so doing, we found that all conditions that involved external music, whether or not combined with sonification, led to a significantly higher synchronization strength, compared to chance level (uncorrected $p < .05$).

Concerning the comparison of the sonification conditions with respect to the other control condition where cyclists had external music only, we observed that the beep condition led to a (marginally) significant increase in synchronization strength. The fact that it is marginally different has to be interpreted again in relation to the used Bonferroni method. The uncorrected *p*-value is .007 and suggesting a medium effect of the beep sonification pattern. On the other hand, the other two sonification conditions – that is, the melody pattern and drum pattern – led to a similar synchronization strength as in the condition where no sonification was present.

Finally, comparing the different sonification conditions, the results showed a significant increase in synchronization strength in the beep condition compared to the melody condition. Again, if we look at uncorrected *p*-values, we also observe a significant difference between the beep condition and the drum condition (uncorrected $p < 0.05$).

Hence, our results indicate that sonification in the form of a beep heard once per rotation at the moment of maximal pedal pressure, contributes to cyclists' spontaneous tendency to synchronize to external music. Hence the question, why is the beep pattern the most effective one? One of the benefits of using a discrete, short beep is that it clearly signals the tempo of the motor rhythm. On top of that, it is a clearly distinguishable signal and avoids that the musical outcome gets too "chaotic" if a cyclist does not synchronize to the external music. This may explain the outcome of our study. In addition, in future research, it could be further investigated whether this finding may be due to the fact that – in the Melody and Drum sonification conditions – cyclists were not acquainted enough with the respective sonification pattern that they had actively under control, throughout the complete trial. Increasing cyclists' acquaintance with the sonification pattern (Melody or Beat), by making part 2 longer for example, could then potentially enhance their synchronization performance in part 4.

Looking at the stability of the cadence tempo of cyclists, we can notice another interesting benefit of using a beep pattern. As the results show, the stability of the cadence tempo became significantly more stable when a beep was provided at the moment of maximal pedal pressure, compared to when cyclists cycled to external music only, without sonification.

Hence, overall, the results of our study suggest that sonification by means of a beep pattern provides a solid basis to "attract" cyclists to synchronize to music and to keep a steady pedal cadence. At this point however, it could be argued that adding a beep pattern in the external music of condition 4 (no sonification) would provide an equally strong rhythmic tendency to the movement and synchronization of movement, as when the beep pattern is used as sonification of the motor rhythm. Hence, in order to make more conclusive claims about the effects of sonification, further research should be conducted. In particular, it would be of interest to investigate whether a similar beep pattern, included into the external music of condition 4, would lead to similar results. Although the results of this study are rather exploratory and preliminary in nature, we believe that it opens new avenues for research on motor learning and adaptation, and has the potential to provide deeper insights into the underlying mechanisms of (spontaneous) auditory-motor synchronization.

6.3.4 General discussion

Music-based methods are useful for movement learning and adaptation in domains such as sports, motor rehabilitation, and active living (Maes et al., 2016). Thereby, methods start to incorporate principles borrowed from the reinforcement learning paradigm. Central to this paradigm is the idea that people can be motivated to exhibit desired behavior by associating a reward to this behavior. In music, important sources of reward are synchronization and entrainment mechanisms (Huron, 2006; Phillips-Silver et al., 2010; Leman, 2016). Synchronizing movements to music feels pleasant and people often exhibit a spontaneous tendency for this behavior. In that regard, synchronization and entrainment mechanisms have been proven useful in musical strategies to “attract” rhythmic movement towards specific target tempi, i.e. musical strategies for spontaneous (uninstructed) tempo adaptation (Maes et al., 2015; Van Dyck et al., 2015; Buhmann et al., 2016; Moens et al., 2014; Moens and Leman, 2015). However, several studies on running and walking have demonstrated that substantial differences exist in the degree that people respond, and adapt their behavior, to music (e.g. Van Dyck et al., 2015; Buhmann et al., 2016). Also research on interpersonal synchronization of movements finds that some pairs of individuals spontaneously entrain much more to each other than others (Nessler et al., 2011; Lumsden et al., 2012). Yet, at this point, it stays an open question which measures and factors could be predictive of these differences in responsiveness and spontaneous synchronization. Hence, as a substantial group of people is not so responsive to music and musical strategies for motor adaptation, there is room for improvement. Therefore, in the current article, we introduced an elaboration of synchronization-based strategies for uninstructed tempo adaptation, based on the principle of sonification. The basic assumption of our approach was that we can further enhance people’s tendency to “lock to” an external musical beat, if they have an active musical contribution to the music. We applied this strategy in the context of cycling. By sonification of cyclists’ motor rhythm, we brought this rhythm into the audible domain, and cyclists were able to contribute musically to the external music. The essential assumption was that synchronization of the motor rhythm to the external music is likely to be a highly rewarding state from a music listening point of view (hence, “attracting” behavior), as the musical layers of sonification and external music are in sync, merging into a coherent musical whole. To us, this strategy is of interest as it applies fundamental knowledge of sensorimotor control in relation to reward mechanisms (prediction mechanisms, sense of agency, empowerment, etc.).

In the current article, we tested this strategy in the context of cycling. For that purpose, we designed an interactive sonification device, the SoundBike, that allowed the sonification of cyclists' motor rhythm. The SoundBike is equipped with sensors to accurately measure pedal crank position and pedal pressure, based on which we can sonify a cyclists' motor rhythm. Implemented on the SoundBike are two distinct but compatible sonification methods. One is based on the principle of "traditional" step sequencers, the other is based on the Kuramoto model, which provides highly effective algorithms for continuous phase-alignment of music to motor rhythms.

In an experiment, we tested the effect of different sonification patterns on cyclists' spontaneous tendency to synchronize to music. The results of this experiment demonstrated that sonification by means of providing a short beep sound at the moment that maximal pedal pressure occurs within a rotation, may reliably increase cyclists' tendency to synchronize to external music. In addition, we found that pedal cadence became more stable in comparison to when no sonification was available (only external music). These results are highly promising for further developing strategies for spontaneous (uninstructed) tempo adaptation of rhythmic, repetitive movements. However, some improvements could be realized. First, although there are clear tendencies, experiments with larger sample sizes are required to allow more conclusive interpretations. In so doing, it would be of interest to also investigate different populations, for instance based on their musical or sports background, to test for effects. Also, we believe that there is room for improvement to make sonification patterns more interesting. As our results indicated, the beep pattern is a strong basis for "attracting" cyclists towards an external musical tempo, but it is obviously not especially interesting from a musical point of view. Therefore, we propose to add additional, more musically interesting sonification layers, such as melodies, bass lines, etc. However, based on our results, we believe that this is only effective once synchronization is achieved, as extra musical reward, to avoid that the musical outcome becomes too chaotic if one is not in sync. Third, as discussed earlier, we should include additional conditions in order to investigate whether strong rhythmic (metronome-like) auditory information included in the external music, may lead to increases in synchronized behavior in similar (or different) ways compared to when this rhythmic information is provided by means of sonification of the motor rhythm. Finally, our strategy should be tested in the context of tempo adaptation. In the scope of the current study, we focused on the development of a sonification strategy to enhance synchronization to external music, as a fundamental prerequisite for adaptation strategies based on synchronization mechanisms (Maes et al., 2015; Van Dyck et al., 2015; Buhmann et al., 2016; Moens et al., 2014; Moens and Leman, 2015). As we succeeded in this, we believe to have a strong basis to design follow-up studies in which tempo adaptation is the actual focus.

Sonification strategies for tempo regulation and adaptation may be useful in various cycling performance tests that assess the interrelationship between pedal frequency, power output, and energy expenditure, which often require to keep, or change to, specific pedal frequencies. A widely accepted test in the field is the incremental test to exhaustion (Bentley et al., 2007). In this test, cyclists start at a specified workload (expressed in watt, W), which is then incrementally increased (expressed in W/min) until voluntary exhaustion. Typically, during this procedure, effects are assessed related to physiological variables (e.g. oxygen uptake and ventilator thresholds) and biomechanical variables (e.g. muscle activity and joint kinematics). In addition, next to performance testing, sonification strategies for tempo regulation may be useful in cycling disciplines where a steady and constant pedal frequency is required, such as in track and road time trials. Currently, both in performance tests and time trials, cyclists almost exclusively rely on visual feedback (of pedal frequency or power output) to regulate pedal frequency. However, the strategy of regulating pace based on auditory-motor synchronization principles may provide a valuable alternative to a strategy that requires explicit and intentional visual attention and processing. On top of that, music has the benefit to motivate people, and may distract from boredom, fatigue, and pain. Apart from using the SoundBike as an interactive sonification tool for assisting motor learning and adaptation, it is being in artistic contexts as well (Maes et al., 2018). Next to the sensors used for measuring pedal crank position and pedal pressure, other sensors are mounted to measure left-right balance, and handlebar pressure. This makes of the SoundBike an intuitive, embodied interface for musical expression, used to control expressive features of music, such as tempo, dynamics, filtering, etc. In addition, multiple SoundBikes can be combined to allow expressive musical interaction in a social context, opening new perspectives for participatory sense-making in music linked to new forms of interaction.

7
Conclusions

In this dissertation we presented several music-based biofeedback systems and their application in sports practices. The basic concept behind all the presented feedback systems is the use of music and music alterations, in terms of movement-to-music synchronization and audio quality modifications to alter/improve the specific physical parameters of the sports under analysis. Movement alterations aim at improving movement technique to reduce the risk of injuries and/or to increase performances. This chapter provides a global overview of the results. We also present some limitations of our studies and give a short note on possible future developments.

7.1 Relevance of the studies

As pointed out in the introduction chapter of this dissertation, most technological devices currently used in sports practices are prevalently used as monitoring tools. Data are acquired during performances and analysed in a posterior phase by trainers and physiotherapists. This limits practitioners' autonomy and further introduces human-dependent variability in the way these data are analysed (Adesida et al., 2019).

Although the use of auditory feedback is gaining attention in recent years (Dubus and Bresin, 2013), as indicated by Bevilacqua et al. (2016), the technology used in these studies remains generally rudimentary (mostly based on alteration of parameters such as audio energy and pitch) and interdisciplinary research is needed to design effective movement sonification for sensori-motor learning.

In the presented works we have shown that reward-based systems which rely on alteration of music properties can effectively be used as auditory feedback. These results confirm the findings of Bergstrom et al. (2014) on the usability of music as biofeedback and further extends its applicability to sports activities.

The positive outcomes of the present studies suggest the possibility to develop reward-based feedback systems for non-instructed motor (re)training programs in ecological environments. These could be implemented as music apps for portable devices and could be targeted to different physical parameters and different sports practices.

Hereafter we present a list of the main achievements and contributions to the research field.

- The proposed feedback system based on superposition of pink noise on top of a tempo-synchronized music track was able to increase running SPM by about 7% with respect to the runners' comfort SPM. Comparison with verbal instructions by a trainer revealed that the effect of the music-based feedback produces larger movement alterations compared to verbal instructions.

- The same feedback type used for reduction of foot strike impact loading was able to reduce impact loading (APTA) by about 27%, without influencing running cadence or speed, in a single retraining session. Previous studies achieved similar results by using combined visual and audio feedback in laboratory setting and after multiple retraining sessions (Clansey et al., 2014).

- When looking at weightlifting movements, our feedback strategy was able to improve movement execution parameters. Specifically, these improvements corresponded to about 10% spine bending reduction and increased horizontal barbell-to-toe distance by over 50% of the initial distance, which suggest a reduced risk of injuries. The biofeedback system performed equally good as one-to-one instructions by a trainer in terms of both movement improvements and motivational characteristics.

- While the effects of music synchronization during running have been mostly analyzed in regards to performances and motivational aspects (Bood et al., 2013; Simpson and Karageorghis, 2006), in chapter 2 we focused on biomechanical parameters alterations. Results have shown that synchronization of the music beats with foot strikes has no direct influence on running impact loading. However, music by itself was shown to induce higher impact loading compared to running in silent. This is a relevant result for the design of music-based biofeedback systems and should be taken into account while designing systems aiming at altering gait parameters.

- The results of chapter 6 have shown that the addition of an active musical contribution through movement sonification may increase the tendency of cyclists' to synchronize to external music and keep a more stable pedalling cadence.

- The sports we took into consideration in the present work are: running, biking and weightlifting. These are three increasingly common sports with over 50 million recreational runners and around 50 million people biking everyday in Europe in 2018. This indicates that results might have large-scale implications on (re-)training practices.

7.2 Answering the research questions

The experiments described in the different chapters aimed at providing answers to our empirical research questions presented in the introduction chapter. Hereafter the main questions are presented together with the answers provided by our experimental results.

Are our music-based biofeedback systems able to induce movement technique changes/improvements without providing explicit instructions? Yes, results of the experiments have shown that the presented systems are indeed able to alter movement parameters without participants being instructed on how to achieve this.

Can these system be used by individuals who are eager to learn or improve their technique but do not have access to sport facilities or to trainers? And how do they compare to standard training methods? This question motivated the design of the experiments of chapters 3 and 5. In the first experiment verbal instructions by a trainer were compared to a continuous music-based feedback to increase running SPM. The overall SPM increase for the feedback condition was significantly higher compared to verbal instructions. In the second experiment two independent groups were used, one receiving instructions by an instructor and the other receiving our music-based biofeedback. In this case, the movement improvements promoted by the feedback revealed no difference between the two feedback types: instructions by a trainer and our music-based biofeedback. In summary, our proposed feedback systems performed as good or better than instructions by a trainer for these specific applications and this positively answers the above research question.

Are these systems effective for different sports or physical activities? Yes, application of similar music alteration techniques to different sports disciplines indicated that the proposed musical reward-based systems are able to modify physical parameters relative to different sports disciplines. Different music-based feedback types were used for the different disciplines to better relate to the specific movement parameters.

Are these systems pleasurable for the users and do participants find them more motivating than standard learning techniques? Results of the questionnaires have shown that our reward-based feedback systems are indeed able to stimulate participants. In the experiment of chapter 3 participants reported that the system introduced a rewarding (game-like) mechanism able to distract from effort. In this case most of the users pointed out that they would use such a system for training practices. In the experiments of chapter 5 some of the more experienced participants reported to be able to discover details of their own movements of which they were not aware of and on which they never received feedback.

7.3 Limitations and future developments

The proposed biofeedback systems were able to produce movement alterations during the feedback sessions. However, neither repetitions of the tests, nor retention tests about the learned parameters were performed. Specific tests should be dedicated to see the efficacy of the systems in long-term applications. Due to the successful results of the proof-of-concept experiment using the pink noise-based biofeedback system of chapter 4, the system is currently being employed by the Department of Movement and Sports Sciences of Gent University in multi-session experiments aiming at gait retraining for running impact loading reduction. These tests could shed light on the retention effects of the proposed feedback system.

In the case of the experiments of chapters 3 and 4 the authors agreed that further developments of the systems were needed to improve portability and ergonomics of the system. A wireless version of the accelerometer system used in the experiments of chapters 3 and 4 has been developed at the Department of Movement and Sports Sciences of Gent University together with IDLab and IPEM. This noticeably increases the ergonomics of the system and will replace the wired system in further experiments.

Although the current biofeedback systems have shown to be effective in achieving the target movement alterations, motivational properties of the auditory feedback could be more thoroughly explored. The use of music distortion although effective for specific applications could be perceived as not motivating/disturbing in the long-term, especially for hardly achievable targets. Alternative reward mechanism based on other music properties (e.g. harmony, melodic structures or audio richness) could be implemented to achieve higher motivational qualities. The choice of the baseline music could further benefit from extension and tailoring of the music database as reported by Buhmann (2017). This could further increase the motivational qualities of the music-reward process.

In the majority of the presented experiments, parameters and threshold values for sonification were manually adjusted by an operator at the beginning of the experiment, according to empirical findings and considerations. Noticeable improvements in this direction could derive from the implementation of automatic movement classification algorithms trained on a wider panel of subjects. Movements characteristics leading to incorrectness could then automatically be detected and corresponding sonification levels associated. This approach would further extend applications of the systems in ecological setting without supervision of an operator and would further minimize variability of the feedback. A database with labeled movements has been created from the experiment of chapter 5 and could be used for further developments.

In the study of chapter 3, a clear difference could be observed between the so-called *responders* and *non-responders*. Responders featured positive reactions to the music-based feedback system while non-responders often had scarce to null effect. No correlations between (non)responsiveness and other quantitative or qualitative data were found in the present case. This phenomenon, also reported in the work of Moens (2018), constitutes one of the biggest open questions in several applications of auditory biofeedback and would deserve proper handling and further investigations (see also Bevilacqua et al., 2016).

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