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RHYTHMIC-BASED AUDIO-HAPTIC FEEDBACK FOR MOTORIC TASKS

BY
JUSTYNA MACULEWICZ

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Rhythmic-based audio-haptic feedback for motoric tasks

PhD Dissertation

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To My Parents, Michał, Barbara, Zosia, and Tymek,
for endless love and acceptance.

Dla Moich Rodziców, Michała, Barbary, Zosi i Tymka,
za nieskończoną miłość i akceptację.

Author CV

Justyna Maculewicz is a PhD fellow at Aalborg University Copenhagen. Her research interests include rhythmic motoric tasks with auditory and haptic feedback. Maculewicz received a BS in acoustics and MS in cognitive science from Adam Mickiewicz University in Poznan. She is focused on research on ecologically valid audio and haptic feedback and its influence on tempo – based exercise for entertainment and rehabilitation.

Abstract

This thesis focuses on rhythmic performance with auditory and haptic feedback. Through the studies on walking and cycling I have been investigating the concept of applying ecological feedback to interactive performances. The first six studies focus on walking interaction and two remaining present an evolution of a concept of rehabilitation system with a stationary bike as a core. Through the literature reviews, I analysed the issues, but as well potential advantages of using auditory or haptic feedback in those two activities. Both of them are crucial to investigate from several reasons. Both of them are inherently rhythmical and share some kinetic functions, which make them complementary. Especially training on a stationary bike (which is easier than walking) can help to exercise elements (e.g. reciprocal flexion and extension movements of hip, knee, and ankle), which are crucial in walking.

The emphasis was placed on ecological sounds utilisation due to their ability to transfer richer information than simple metronome-like sounds. They are already associated with motor actions, which adds a motivational aspect, and gives a chance to recreate a close to real auditory experience when combined with soundscape sounds. Since, walking and biking share similar kinetic patterns, improved biking performance can as well lead to improved gait patterns. Thus, systems which introduce higher motivation to exercising are desired to be developed.

The main novelties, which this thesis contributes with are 1) a usage of ecological feedback and cueing in rhythmic interaction, which until now did not receive enough attention, unlike the non-ecological feedback; 2) investigation on tactile interaction within rhythmic walking scenario; 3) the first study on the influence of soundscape on rhythmic walking interaction with a focus on a preferred pace; 4) the first study on monitoring brain activity while walking with following ecological vs. non-ecological rhythmic cues; 5) a concept of a design of an audio augmented stationary bike-based system for rehabilitation.

The results of the studies present interesting outcomes and reveal promising paths for future work. They are especially interesting in a context of motivation exercising for elderly and gait rehabilitation. The research which will follow this thesis will be focused on expanding knowledge in the areas which have already been investigated and applying the obtained results in everyday usage in exercising and rehabilitation.

Resumé

Denne afhandling fokuserer på rytmisk præstation samt auditiv og haptisk feedback. Igennem mine studier af gang og cykling har jeg undersøgt, hvordan begrebet naturlig feedback kunne anvendes i forbindelse med interaktive præstationer. De første seks undersøgelser i mit projekt fokuserer på interaktion ved gang og de to resterende undersøgelser præsenterer en videreudvikling af konceptet: rehabiliterings system med en stationær cykel som kerne. Gennem litteratur studier er problemstillingerne blevet analyseret med fokus på potentielle fordele ved brug af både auditiv og haptisk feedback på disse to aktiviteter. Det har været afgørende at undersøge begge aktiviteter af flere grunde. Begge aktiviteter er ifølge sagens natur rytmiske og deler nogle kinetiske funktioner, som gør dem komplementære. Især træning på en stationær cykel (som er lettere at bruge end at gå) kan hjælpe med at udøve forskellige trænings elementer (fx gensidige bøjninger og udvidende bevægelser af hofte, knæ og ankel), som er afgørende, når man går.

Hovedvægten af den auditive del af træningen er blevet baseret på naturlig lyd på grund af dennes mulighed for at overføre en bedre lyd end simple metronom-lignende lyde. De naturlige lyde er således allerede forbundet med motoriske handlinger, som tilføjer et motiverende aspekt, og som giver mulighed for at skabe en ægte auditiv oplevelse, når de kombineres med lyde fra et lydlandskab. Da gang og cykling deler kinetiske mønstre, kan forbedrede cykel - mønstre føre til forbedrede gang - mønstre. Derfor har det også været ønskeligt at videreudvukle systemer, der tilfører højere motivation til træning.

Det nye, som denne afhandling bidrager med, er 1) en anvendelse af naturlig feedback og signalering i rytmisk samspil, som indtil nu ikke har fået tilstrækkelig opmærksomhed, i modsætning til den ikke-naturlige feedback; 2) undersøgelse af taktil interaktion inden for rytmisk gang scenarie; 3) den første undersøgelse af lydbilledets indflydelse på rytmisk gang interaktion med fokus på et individuelt foretrukket tempo; 4) den første undersøgelse om monitorering af hjerneaktiviteten, mens man går med følgende naturlige vs. ikke-naturlige rytmiske signaler; 5) et design koncept af et lyd augmenteret stationær cykel-baseret system til genoptræning.

Afhandlingens resultater er interessante og lovende for et fremtidigt arbejde. Resultaterne er særligt interessante i forhold til at skabe motivation og forbedring af ældres gang i forbindelse med rehabilitering. Den forskning, der vil følge denne afhandling, vil være fokuseret på at udvikle og etablere viden på de områder, som allerede er blevet undersøgt, samt vil også blive brugt på undersøgelse af anvendelsen af de opnåede resultater i dagligt brug i udøvelsen af træning og rehabilitering.

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Thesis Details

Thesis Title: Rhythmic-based audio-haptic feedback for motoric tasks

PhD Student: Justyna Maculewicz

Supervisors: Prof. Stefania Serafin, Aalborg University
Prof. Lise Busk Kofoed, Aalborg University

This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers that are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

Contents

Part I

Introduction

Motivation

This thesis is the result of three-years-long studies on rhythmic interaction with auditory and haptic feedback. A series of literature reviews and experiments are presented in eight main articles which were chosen to form this thesis. The main motivation for the studies which constitute this thesis was the general need for rehabilitation and exercising techniques which improve persons' rhythmic motor performance and heighten motivation to exercise. Two branches of research are emerging under the main topic unveiled in the thesis title. The first one refers to an examination of rhythmic walking interactions and the second to an attempt of designing a stationary bike-based rehabilitation system. Walking and biking are both inherently rhythmic actions and can be affected and motivated by a usage of auditory and haptic feedback with an addition of soundscape sounds. The main novelties, which this thesis contributes with are 1) a usage of ecological feedback and cueing in rhythmic interaction, which until now did not receive enough attention, unlike the non-ecological feedback; 2) investigation on tactile interaction within rhythmic walking scenario; 3) the first study on the influence of soundscape on rhythmic walking interaction with a focus on a preferred pace; 4) the first study on monitoring brain activity while walking with following ecological vs. non-ecological rhythmic cues; 5) a concept of a design of an audio augmented stationary bike-based system for rehabilitation.

The results of the studies are important in a context of interactive walking stimulation. Especially, when we think about gait rehabilitation. This research introduces the analysis of an utilisation of the ecological sounds. The emphasis was placed on ecological sounds due to its ability to transfer richer information than simple metronome-like sounds. They are already associated with motor actions, which adds a motivational aspect, and gives a chance to recreate a close to real auditory experience when combined with soundscape sounds. Since, walking and biking share similar kinetic patterns, improved biking performance can as well lead to improved gait patterns. Thus, systems which introduce higher motivation to exercising are desired to be developed.

In the following sections, the readers will find a selection of the chapters, which will guide them through the motivation and background knowledge needed to understand the reasoning behind the studies and to place the presented research on a scientific map. The following chapters on research questions, summary of the methods and discussion will outline the achievements and present the highlights of the articles. These chapters serve as an introduction and appetizer to the main part of the thesis - the articles already published (papers: B, C, F, G, and H) or submitted to be reviewed (A, D and E). Below, the readers will find an elaboration on the motivation which driven each branch of the research.

1 Investigating Interactive Rhythmic Walking. Behavioural and Neurological Perspective

The specific goal of the first group of research was to focus on the techniques for walking interaction with ecological feedback. Based on the inspiration from the studies on ecological feedback [88, 115] and driven by the need for more efficient gait cueing techniques, the area of rhythmic walking has been explored.

It is well known that humans are able to time their movements to sounds patterns with a high degree of accuracy [87]. This is also true in fundamental rhythmic activities such as walking. Rhythmic interaction, defined as the ability to follow or produce a certain pace, can be manipulated by presenting different cues and forms of feedback. In recent years, research on the role of auditory feedback in walking has received an increased attention. Specifically, it has been shown that following a rhythmic auditory (metronome-like) cue helps gait performance in patients with Parkinson's disease (PD). External rhythms presented by auditory cues may improve gait characteristics, and can also be used to identify deficits in gait adaptability. Walking pace and step length are the characteristics of gait, which should be guided by sensory cues during gait rehabilitation. The general goal of the presented research is to test rhythmic interactive walking with auditory feedback from several perspectives. From a quantitative perspective, to investigate how different types of auditory cues influence tempo stability within different pace range and how the feedback and soundscape sounds (all sounds within a location, which constitute sound environment and provide information on it) can influence preferred pace of participants. From a qualitative – to see how different feedback, cues and soundscapes can shift the perception of naturalness and perceived ease of synchronisation and walking in general. The focus was placed on the ecological sounds (sounds which might be encountered in everyday life, such as walking on different ground materials e.g. gravel or wood), which are seen as the signals, which convey richer and more useful information than just simple metronome clicks.

2 Towards an Auditory Augmented Bike-Based Rehabilitation System

Exploring ways to improve rhythmic walking performance was the motivation of the first group of articles. Two papers which constitute the second branch are focused on a rehabilitation system with a stationary bike as a central component. Since many people in their advanced years can not or are afraid of exercising or even just going out of their apartments or healthcare institutions, there is a need to focus on designing exercising system, which will be motivational and will help to improve physical health. In these studies, the exploration was focused on a stationary bike, which is an easily accessible exercising equipment. While reviewing already existing systems with a stationary bike, its wide usage in virtual reality and rehabilitation scenarios was encountered. Walking and biking are both inherently rhythmical and share similar functions. The usage of ecological feedback and soundscape were proven to manipulate walking performance, thus it was assumed that similar effect could be achieved while exercising on a stationary bike. It was also believed that appearance of these sounds can heighten motivation to exercise and make the training sessions more enjoyable and, thus, longer.

The following background chapter describes all of the terms and phenomena which the included articles in the thesis refer to. It is crucial to introduce them to fully understand the foundation of the forthcoming scientific questions and to be able to discuss the results in the wider context and refer to the effects which motivated from the beginning the execution of the studies. All of the sections included in the background chapter are connected to a varied extent with the content of the studies. Sections such us *Sensorimotor Synchronisation* or *Rhythm and Tempo* are drawing the wider context of the research and place the studies on a scientific map. On the other hand, sections such us *Walking* or *The Role of Soundscape Stimulation* are more directly linked to the articles and present introduction to what will be described in the forthcoming articles.

Background

3 Walking

"Walking is a natural act, our default and intuitive way of transportation. It is commonly performed in an absence of conscious attention; walking is a way of transportation, of getting somewhere, but it is also a way of exploration and experiencing space. It unconsciously adjusts to a particular context or task whilst being performed." This excerpt comes from a very inspirational work of Wunderlich [61] and, in my opinion covers the most important aspects which define the action of walking. By walking through places we establish our attachment to them [54]. We draw our image of the place with a set of metaphors, sentiments, emotions and memories. Walking helps us to understand the space [61]. Wunderlich [61] mentions three types of walking which people perform: the purposive walking (constant rhythmical and with rapid pace), discursive walking (more varied spontaneous rhythm) and conceptual walking (reflective walking; a response to our interpretation of place). Walking is an activity that plays a very important part in our daily life. In addition to being a natural means of transportation, it relates to the core human abilities including motor control, rhythmic perception and production, sensorimotor synchronisation, social aspects, and physical exercise. Walking is also characterised by the resulting sound, which can provide information about the surface, type of shoes, and movement speed as well as the person's age, weight, gender, and physical conditions (e.g. [51, 28, 107, 99]).

3.1 Rhythmic Walking

Walking is inherently rhythmical. It is affected by internal bodily rhythms as well as external place-rhythms (slow or fast character of the place) [61]. The studies included in this thesis are mostly focused on the auditory interaction with the environment with some additional tactile influences. It is well known that humans are able to time their movements to patterns of sounds with a high degree of accuracy. This is also true in fundamental rhythmic activities such as walking. Rhythmic interaction, defined as the ability to follow or produce a certain pace, can be manipulated by presenting different cues and forms of feedback. Research shows that humans are able to synchronise to music in a broad range of tempi. The most optimal synchronisation happens at around 120 beats per minute [97]. Moreover, recent studies show that recurrent patterns of fluctuation affecting the binary meter strength of the music may entrain the vigour of walking movement [50]. Recent research investigating the role of music on temporal aspects in walking behaviour in an urban settings, showed that music affects the walking tempo, although the beat did not lead to precise synchronisation [25]. Moens et al. [71] demonstrated that walkers can synchronise to the musical beat without being instructed to do so when a special interactive music player is used, which identifies the individual's walking tempo and phase and adapts the music accordingly.

3.2 Walking with Auditory Feedback

Studies of human perception of locomotion sounds have addressed several properties of the walking sound source. The sound of footsteps conveys information about walker's gender [51, 27], posture [76], emotions [27], the hardness and size of their shoe sole [27], and the ground material on which they are stepping [28]. Despite the interesting discoveries, the investigation of ecological feedback are still in the initial phase when referring to rhythmic walking. Ecological signals have the possibility to convey richer information than only a person's pace. Rhythmic sounds (metronome-like) only specify step duration of gait, with no information relating to spatio-temporal properties of walking actions. Complex walking sounds, such as footsteps on gravel, may convey both temporal (step duration) and spatial (step length) properties of gait [88]. Auditory feedback has also the strength to change our behaviour. Studies show that interactive auditory feedback produced by walkers affects walking pace. In the study of Turchet et al. [108] individuals were provided with footstep sounds simulating different surface materials, interactively generated using a sound synthesis engine [75]. Results showed that subjects' walking speed changed as a function of the simulated ground material.

3.3 The Advantages of Haptic Stimulation

When considering a multimodal scenario, previous research investigating the interaction between auditory and haptic feedback in footstep sounds has shown that the same simulation algorithms can be adopted to provide auditory and haptic feedback [107]. Both auditory and haptic feedback are represented as temporal variations, which can be simulated with similar patterns, at different frequency ranges.

Little research has focused on foot-based vibrotactile systems. The sensitivity of the sensory system of the feet is sufficient for vibrotactile guidance [106]. Signals from mechanoreceptors in the foot are one of the main sensory sources for gait generation and modification [78]. It is likely that mechanoreceptive afferents in the sural nerve provide rich information about contact patterns between the foot and the environment during stance and locomotion [106]. When exposed to audio and haptic stimulation, subjects are able to best recognise different materials delivered haptically or as a combination of auditory and haptic feedback [29]. Since most of the pedestrians wear shoes when walking it makes it an excellent platform for mounting actuators [113].

Articles B and C explore the utilisation of auditory and haptic feedback in rhythmic walking interaction. They follow assumption of richer ecological audio signals and investigate the additional influence of haptic feedback.

3.4 Gait Rehabilitation Through Auditory Stimulation

Metronome-like Rhythmic Stimulation

It has been shown that following a rhythmic metronome-like auditory cues helps gait performance in patients with PD [101, 64, 98, 89, 102]. The PD patients are usually provided with an auditory metronome, or markedly rhythmic music, and asked to match consecutive footfalls with the onset of each beat [88]. External rhythms presented by auditory cues may improve gait characteristics [98, 89, 102], and can also be used to identify deficits in gait adaptability [7]. Spaulding et al. [93] in their review pointed that the auditory cueing elicited positive changes in gait cadence, velocity and stride length.

Mutual Entrainment

The aforementioned way of stimulation lacks the interactivity component where the system could adapt to the user. The way to overcome this issue is to implement the principles of mutual entrainment, which occurs when at least two 'partners' adapt to each other's period and phase of motor action. These can be both humans and digital systems which are programmed to adapt to the user's rhythmic behaviour. Miyake [67] proposed the Walk-Mate to implement the mutual entrainment for the rehabilitation of PD and hemiplegic patients. Baram [8] suggested that gait rehabilitation must be performed in a closed-loop system to avoid constant vigilance and need of attention strategies to prevent reversion to impaired gait patterns caused by repetitive stimuli. Hove et al. [38] reported that random, disconnected stride times (low fractal scaling) predicts falling for PD patients. Fixed rhythmic auditory stimulation lowers fractal scaling and requires attention. Gait rehabilitation should lead to achieving the more stable and not random stride times structure, which can be observed in healthy gait [38]. Systems based on mutual entrainment principles can emergently respond to unpredictable changes in human behaviour [69]. The studies by Hove et al. [38] and Uchitomi et al. [109] showed that the gait fluctuation of the patients gradually returned to a healthy stride times fluctuation level in the interactive conditions. This effect did not occur in fixed tempo and no-cue conditions.

4 Gait and Cognitive Control

Gait is a complex motor activity that places demands on sensory and cognitive systems [90]. Walking has more in common with complex motor tasks, like catching a moving object (an act that utilises complex cognitive resources and executive function such as estimation, planning, real-time adjustments), than it does with tapping [35]. Based on the brain imaging studies it can be concluded that activation of areas related to higher cognitive control occurs during actual [34], imagined [6] and simulated [23] walking. The results of the meta-analysis [1] of dual-task studies emphasise the role of high-order cognitive systems in gait control. A few gait characteristics can be affected by the second task performance. More specifically, dual-task-related changes in spatio-temporal gait parameters include decreased speed, decreased cadence, decreased stride length, increased stride time, and increased stride time variability [1]. Srygley et al. [95] showed that walking affects the cognitive performance and vice versa when participants are not instructed to focus on one of those tasks. They proved as well that walking affects cognitive performance much stronger in adults. As they explain this can be due to need of focusing on two attention-demanding tasks. The capacity-sharing theory [105] suggests that in this situation both tasks will suffer due to limited information processing.

5 The Role of Soundscape Stimulation

The term soundscape was introduced by R. Murray Schafer in 1960s and the research on this topic was pioneered by The World Soundscape Project (WSP) - an educational and research group established by R. Murray Schafer at Simon Fraser University. According to The International Organization for Standardization (ISO) soundscape is a perceptual construct, related to but distinguished from a physical phenomenon (acoustic environment) (ISO 12913-1:2014). Soundscape exists through human perception of the acoustic environment. The working theory used in The Positive Soundscape Project [19] includes the important aspects of the soundscape and focuses on its perception: *"the totality of all sounds within a location with an emphasis on the relationship between individual's or society's perception of, understanding of and interaction with the sonic environment".*

Immersing people into soundscape sounds was proven to improve patient's health [52]. Lindborg et al. [52] investigated the relationships between soundscape features and physiological responses linked to relaxation and stress. They found out that peripheral temperature was negatively correlated with loudness and with calm-to-chaotic scales. Their results indicated as well heart rate (HR) negatively correlated with timbral brightness and fluctuation strength. They explained this effect by a correlation of high temperature (indication of reduced system activation) and low heart rate with relaxation and low peripheral temperature with stress. Hume and Ahtamad [39] monitored HR and respiratory rate (RR) while listening to pleasant and unpleasant soundscapes. HR was lowered and RR raised as an effect of this listening task. More specifically, more unpleasant soundscapes caused larger false in HR and the pleasant soundscapes caused greater rise in RR.

The results of The Positive Soundscape Project, which are summarised in [19] indicated that humans' assessment of soundscapes is driven by high-level cognitive features rather than low-level acoustic characteristics. The meaning and emotions carried by the soundscape sounds are the main indicators of what people perceive as positive or negative soundscape. It is important that natural sounds and human sounds are incorporated into the soundscapes. Similarly, in the research of Dubois et al. [20] soundscapes with human activity were perceived as more pleasant than those with predominant mechanical sounds. Further results of The Positive Soundscape Project indicated participants' need of having behavioural and cognitive control over it. Soundscape sounds should provide information and the sounds comprising the soundscape should not require listeners attention. If the soundscape requires more attention allocation (by being loud or persistent) it tends to be perceived as negative. Sounds, which 'blend together', are assessed as positive. Memory of a past event also influences the evaluation in a significant way. The authors claim that distinction between sound and noise in a context of soundscape is rather emotional and two dimensions, calmness and vibrancy, seem to be responsible for this emotional response [19]. Research on combined landscape and soundscape also draw interesting conclusions in a context of the research presented in this thesis. Brambilla [13] proved that the more the sound is congruent with the listener's expectation, the level of evoked annoyance is lower and its acceptability higher. The rate of acceptability of the sound increases with a decrease of its sound level and detectability of non-natural sounds. Van Renterghem et al. [112] pointed as well that unidentified sound sources are judged differently. Until now no research which assesses human rhythmic behaviour when exposed to the various soundscapes has been performed. The general assumption can be derived from the Boltz's study [12], being that people tend to speed up their preferred tempo when exposed to annoying sounds and slow down when exposed to relaxing music. Franěk [24] monitored persons' rhythmic behaviour when walking in natural environment. They observed that humans walk faster in places without greenery and with a higher level of traffic and noise in places with greenery and with a low level of traffic and noise.

6 Rhythm and Tempo

6.1 Rhythm Perception

Rhythm is a strong, regular repeated pattern of movement or sound [82]. In the literature there are two main theoretical approaches to rhythm perception, which will be only briefly introduced here. The first set of models, interval theories, are associated with cognitive psychology and focuses on the way in which listening incorporates an internal counting mechanism that essentially computes statistics from musical structure [100]. Models developed within this framework consist of distinct clock, memory, and decision stages of temporal processing and have been applied to both perceptual and motor aspects of responding to musical events [65]. The second set, entrainment theories, suggests that rhythms are perceived via process of entrainment, in which one rhythmic pattern achieves and maintains synchrony with another pattern [100]. It proposes that the tempo and rhythm of everyday events engage people on a moment-to-moment basis through attentional synchrony [63].

6.2 Preferred Tempo

In general, tempo can be defined as the rate of something regularly repeating [70]. Tempo helps listeners track musical events as they unfold in time and enables predictions about when future events are likely to occur [62]. Conceptually, rhythm and tempo are independent of each other. Tempo refers to absolute time, when rhythm to the relative one [100].

Fraisse [22] discovered the phenomena of spontaneous tempo, which is highly linked to the concept of the preferred tempo. He found that people are surprisingly consistent when asked to simply tap at the rate that is comfortable. The behaviour varies across individuals but the general conclusion is that humans prefer tempi with a beat period around 600 ms. This rate is similar with the rate at which people walk, but has nothing to do with the person's heartbeat [100]. After 20 years, Moelants [70] showed that the range between 120 and 130 BPM (120 BPM=500 ms) is more realistic for being shown as a preferred one. The tempo limit, which is possible to synchronise with, ranges from 100-300 ms to 2 000-2500 ms (reviewed in: [3, 62]). The limit of fast tempo partly depends on the limits within the motor system [3]. The limit of slow tempo is linked the limits of temporal capacity in working memory [81].

Manipulation of preferred tempo

Differences in preferred tempo are associated with age and between individual fluctuations. Other factors such as gender, handedness, or body size appear not to affect the preferred tempo [62]. In a study of Boltz [12] it was shown that exposure to annoying sounds can increase preferred pace, and in opposite, exposure to relaxing music tended to slow down the tempo. She linked this effect to the level of a general arousal of tested participants.

In a study of Turchet et al. [108], authors explored a topic of affected natural locomotion pattern by the auditory feedback. They tested 3 different sounds of footsteps (walking on snow, gravel and wood) produced on-line based on the information coming from the pressure sensors incorporated into the shoe insoles. The task was to walk normally with the natural gait. The measured values were step time, velocity, elapsed time, steps per minute, number of steps, and step length. The statistical differences were observed for four first factors. The questionnaire analysis revealed differenced in perceived easiness, velocity, effort, and sinking.

Menzer et al. [66] investigated the feeling of control over the footsteps through the delayed feedback. The effect of manipulated walking speed, which was unexpected by the researchers, occurred in parallel to the affected feeling of agency over the footsteps.

7 Sensorimotor Synchronisation

Sensorimotor synchronisation is the coordination of rhythmic movement with an external rhythm [87]. Stevens, in 1886, was the first who studied this topic [96]. This has been mainly done through tapping experiments, where participants are asked to tap in synchrony with stimuli, mainly auditory. The main conclusion from this research is that the synchrony between tap and pacing signal is controlled and established at the central representation level [3, 4]. It means that we do not synchronise the auditory input and the motor output but rather the synchrony is established between perceived click and perceived tap. Based on that, the processing speed of sensory information becomes very crucial [3]. As Białuńska et al. [11] assumed, it happens due to the faster accumulation of sensory information from auditory and visual pacing stimuli than from tactile and kinesthetic feedback from the taps. Since, the tap code needs to coincide with the click code at the brain level, the click and tap cannot coincide in the real world [4]. A phenomenon of a click being preceded by tap is called Negative Mean Asynchrony (NMA). The occurrence of NMA demonstrates that the motion command is generated before the onset of auditory stimuli [68] and suggests that sensorimotor synchronisation is an anticipatory process. Already in 1980 Fraisse [21] observed NMA. He reported as well that NMA produced while foot tapping is even bigger than in hand tapping.

7.1 Resonance Theory and Two Types of Anticipatory Mechanism

Our abilities to synchronise with stimuli presented with a constant pace changes with age and also is different for varied interstimulus-onset interval (ISI). Miyake [68] revealed two types of anticipatory mechanisms by investigating the effects of higher brain functions and attention involvement in synchronisation task. He claims that attention is required for long ISI and shows that synchronisation error (SE) is scaled by ISI in a range of 1800 and 3600 ms. Synchronisation with shorter ISI is an automatic anticipatory process not affected by attention. In a range of 450 to 1500 ms the SE was constant and independent of ISI.

Exploration of our abilities of synchronisation also suggests the existence of resonance curve [111]. Van Noreen and Melons [111] describe this phenomena as: *"the increase in amplitude of oscillation in a physical system exposed to a periodic external force of which the driving frequency (or one of its component frequencies) which is equal or very close to a natural frequency of the system"*. In locomotion it is established at the level of 2 Hz [56, 111] and it is described as preferred tempo, which is the easiest to follow. The resonance curve centred near 2 Hz is very narrow for children and the variability of sensorimotor synchronisation is high. With age our adaptation to various ISIs is improved [18] and the variability of sensorimotor synchronisation decreases [26].

Articles B, C, and E challenge mentioned value of preferred tempo. The discussion of the results of soundscape influence on walking behaviour (paper E) refers to the synchronisation theories. None of them is favoured and, as a matter of fact, these two can be used in explaining obtained effects.

8 The Neural Bases of Rhythm Perception

The brain activation depends on the complexity of the perceived rhythms. The brain activity correlated with the simple rhythms is located primarily in motor areas (the motor cortex and cerebellum). Since, the prefrontal cortex is important for the functioning of working memory and decision-making [100], additional activation in this area is observed when people retain complex rhythms [100]. The more recent studies shown that participants' motor systems are activated when they listen to auditory rhythms without executing any motor task [30, 32]. Basal ganglia is required to perceive the underlying structure of a rhythm, such as a regular beat [31]. Will and Berg [114] showed that isochronous sequence of tones can regulate brain oscillations at slow frequencies (1-5 Hz). In a favour of resonance theory, the highest activity is observed with a stimulus rate of 2 Hz [70]. Not only at the behavioural level but as well at neural level we can observe distinction between 'automatic' and 'cognitively controlled' timing processes. Synchronisation with short intervals seems pretty easy and is supported by cerebellum [86]. Higher brain functions contribute to the perception of time intervals that exceed 2 to 3 seconds [43]. Synchronisation with long intervals engages corticalubcortical loop involving the basal ganglia, parietal cortex, and prefrontal areas [15].

In the article D an electroencephalographic (EEG) method was used and focus was placed on the selected band-waves activation. Below are described the events and characteristics of stimuli which correlate with activation in each oscillation band. The chosen bands are alpha, beta and gamma; respectively associated with a state of rest [10], motor activation [5] and the binding process [48].

8.1 Alpha Waves

Oscillatory activity in the alpha band was first reported by Hans Berger in 1929 [10]. Since then, its activity has been associated with a state of rest. It emerges during rest and increases when subjects close their eyes. Alpha oscillations tend to decrease during activation [47]. It has been suggested that desynchronisation of lower alpha (7 - 10 Hz) reflects general task demands and attentional processes [79] and could be obtained in response to almost any type of task [49]. Shimai et al. [91], amongst few studies about environmental sounds, show that powers of theta and low frequency alpha bands were higher during presentation of the pleasant sounds than during presentation of the unpleasant sounds. However, the alpha activity was more closely related with subjective confidence in the sounds identification than with pleasantness - unpleasantness estimation of the sounds. In general, they claim that alpha activity seems to be closely related to the recognition of the sounds. The occipito-parietal alpha power decreases with the level of transformation of musical tempo, consistently with the behavioural ratings of naturalness [103]. Similarly, Ma et al. [55] found that alpha power change with the naturalness rating of a musical performance. The change in posterior alpha may be related to the possibility that tempo-transformed music is more attention-getting than the original music [103].

8.2 Beta Waves

Beta oscillations are strongly associated with the motor system [5]. Typically, beta oscillations decrease in power in anticipation of sensorimotor processing [110]. It has also been associated with the exchange of information between motor cortex and the muscle [44]. Pavlidou et al. [77] proposed that sensorimotor beta oscillations reflect a mechanism of attempted matching to internally stored representations of movements. Beta power in primary motor cortex decreases by observation of somatosensory stimulation and by observation of goal-directed movements [74]. Voluntary movement causes a decrease in beta power, while an increase in beta power in sensorimotor areas reflects active inhibition of the motor system [77]. An increase of activation in beta wave-band was observed in PD patients with gait disorders [104], which is associated with lower motor control.

8.3 Gamma Waves

Gamma oscillations have been associated with a broad range of cognitive functions that include working memory, attention, object recognition, and perceptual learning [40]. It is typically associated with active neuronal processing of information [41]. There is growing evidence that oscillatory gamma band activity is an expression of the binding process [48]. The 'binding-by-synchronisation' hypothesis proposes that binding is achieved by neuronal synchronisation in the gamma band [41]. In general communication between brain regions should be reflected in gamma band coherence [14].

9 A Stationary Bike for Exercise and Rehabilitation

Both walking and biking are cyclical in nature. These two actions share similar kinetic patterns. They both require reciprocal flexion and extension movements of hip, knee, and ankle, and present an alternating and coordinated antagonist muscle activation [83]. Phadke et al. [80] showed that bicycle training normalises reflex depression, which is as well a shared function with walking. Hence, based on the effect of transfer of function to walking [85] bike exercise can be used as well in walking rehabilitation. Biking may also regulate timing and amplitude of limb movement, which can be helpful for the rehabilitation of freeze of gait - a phenomenon observed in PD [92].

A stationary bicycle is a powerful rehabilitation and exercising device, due to its natural rhythmic component. Indoor exercising on the stationary bike might be a monotonous activity if not supported with some visual or auditory stimulation. The technology inclusive of different types of sensors and interfaces provides us with opportunity to make the stationary bike much more efficient and enjoyable tool. By the addition of auditory stimulation, the stationary bike users can become augmented in the more stimulating and motivational environment which can give both psychological and physiological benefits. Articles G and H present the elaboration on the topic of augmenting a stationary bike with audio and haptic stimulation.

9.1 A Stationary Bike in Rehabilitation

A stationary bike has been used in rehabilitation of cognitive and physical skills in several disabilities and diseases such as a stroke [2, 84, 17], multiple sclerosis [73, 9], spinal cord paresis [17, 16], balance disorders [17, 46, 45] and traumatic brain injury [33]. It also serves as a help for post-surgical population [84]. Specific functions, which might benefit from cycling therapy are a motoric activity, a circulatory system, breathing [17], and balance control [45].

9.2 A Stationary Bike in Virtual and Augmented Reality

Commercially available systems using a stationary bike augmented with virtual reality (VR) have both fitness and rehabilitation applications. Most of them are concentrated on the visual aspects of VR. Systems like Holdings [37], Sports [94] and Mokka et al. [72] are for active individuals to make their fitness more demanding and enjoyable. Also several rehabilitation applications were made with the stationary bike as a core of the system. Ranky et al. [84] introduced Virtual Reality Augmented Cycling Kit (VRACK). It is a combination of a stationary bike and specific hardware and sensors, which allows for data acquisition (e.g. physiological) and stimulation by visual, audio and haptic feedback. Chen et al. [16] has proposed a rehabilitation system with only visual feedback for rehabilitation of spinal-cord injury. Chuchnowska and Sękala [17] developed a system for interactive rehabilitation of children under the age of three.

There is only few studies which concerns only auditory feedback without embedding it into the VR experience. In the work of Liu et al. [53], authors compared the utilisation of auditory and visual feedback in biking. It was proven that adults' accuracy in a control of continuos motor task is higher when performed with auditory than visual feedback. In this study, children were chosen to test the occurrence of a similar effect. For visual feedback, speedometer was presented on the screen and a picture of chosen cartoon character. Auditory feedback was presented in a form cheering sound as well picked by a participant. When the tempo was slower than target cadence, the low pitched sound was played and high pitched was played for too fast cadence. The results show that children responded to auditory feedback with a smaller root means square error and showed enhanced performance in acquisition, retention, and transfer phases.

Research Questions

The chapter on the research questions specifies the goals of the articles. A short motivation for each study and the questions which were attempted to answer are presented. I aimed with this chapter to guide a reader through a chain of investigations which were performed within this thesis and show the connections between them.

Paper A (review): **"A Review of an Influence of Auditory and Haptic Feedback on Rhythmic Performance in Swimming, Rowing, Walking, and Cycling."**

The opening article of this thesis is a review concerning in general rhythmic performance with auditory and haptic feedback. The focus was placed on four types of motor actions, which are walking, rowing, swimming, and biking. All of them are inherently rhythmic. The wide selection of literature had been collected, an the focus was mainly on the studies which show the usage of haptic and/or auditory feedback in real-life usage scenarios and its influence on the users' performance. The motivation was to analyse hitherto applications and answer to a selection of questions which drove the need for this review.

Q1: *What is the goal of using feedback in rhythmic actions?*

Q2: *What type of feedback is mainly used?*

Q3: *What type of information is transferred through the feedback?*

Q4: *How is the feedback perceived by the users and how it influences performance?*

Paper B: **"The Effects of Ecological Auditory Feedback on Rhythmic Walking Interaction."**

The first experimental article presents investigations on walking as a rhythmic action and the effect of auditory feedback on this action, within the framework of closed-loop interactive sonification [36]. The subjects were provided with different auditory cues to guide their gait at different tempi. The tracking footsteps system for providing input data utilised auditory signals captured near the feet with contact microphones. It was decided to use the existing technology for footsteps generation in auditory and haptic domain [75]. The available software allows to produce footsteps sounds whose temporal evolution is calculated using the amplitude envelope of the actual users' footsteps. It was assumed this amplitude envelope corresponds to the ground reaction force. Each specific type of a surface was modelled through physical algorithms. Gravel and wood were used as ecological signals which were recalling sounds emerging while walking on these surfaces. Sine wave was a non-ecological stimuli which in an acoustic structure resembled wood. The aim was to study how different rhythmic cues affect the walking rhythm, thus providing insight into the design of the rhythmic feet-based interactive systems. The consideration was given to the different temporal forms of the feedback, namely direct synthetic response to each step, and both ecological and non-ecological continuous synthetic audio feedback with and without tempo adaptation to the human gait.

Q1: *How different feedback sounds (ecological and non-ecological) and interaction types (constant and adaptive tempo cueing) affect human walking?*

Q2: *How different feedback sounds (ecological and non-ecological) affect preferred walking pace?*

Paper C: **"An investigation on the impact of auditory and haptic feedback on rhythmic walking interactions."**

In the following experiment it was decided to incorporate haptic stimulation to test how it can affect rhythmic interaction. The same algorithms were adopted, since haptic stimulation was driven by an actuator, which performs as a low-frequency speaker.

Q1: *How different auditory events support rhythmic actions, and whether haptic feedback combined with auditory feedback facilitates the synchronisation?*

Q2: *How auditory feedback combined with haptic influences preferred walking pace?*

Paper D: **"The Electroencephalographic Perspective on The Effects of Ecological Auditory Cueing on Rhythmic Walking Interaction."**

The curiosity of how the synchronisation with previously behaviourally tested signals will be represented in cortex activation driven the design of an electroencephalographic (EEG) experiment to capture the neural activation. The strict design of EEG experiment forced a usage of one more acoustic signal, which was as well non-ecological but in acoustic structure resembled aggregate nature of gravel sound. It was assumed that both 105 BPM tempo and ecological sounds should cause increased alpha activation. Performing preferred tempo should be the easiest task and need less attention than the others. It was expected to acquire similar results for ecological ground materials. Beta oscillations were chosen for analysis since their activation is strongly connected with motor behaviour. Since, both gravel and wood sounds are easy to encounter in real life as a feedback of motor task, beta oscillations were expected to decrease while following these stimuli. The assumptions for gamma oscillations activity were not unequivocal. Since gamma oscillations are believed to be responsible for binding information from different brain regions at least three different hypothesis refereeing to object recognition, congruency between modalities and analysis of the structure of the stimuli could have been assumed. Respectively, it was possible to obtain an increase in gamma activation for ecological materials, both solid sounds or both aggregate sounds.

Q1: *How are the differences in brain activity within specific frequency bands shaped when participants are synchronising with ecological and non - ecological auditory cues in three different tempi?*

Q2: *What re the potential neurological explanation for the effects occurred in previous behavioural studies?*

Paper E: **"How Can Soundscapes Affect the Preferred Walking Pace?"**

The following soundscape study was a behavioural experiment where feedback and soundscape sounds were combined to monitor preferred pace of the participants. The designed experiment was motivated by the results of the first three experimental studies (papers: B, C and D) and driven by the desire to explain the obtained effects. Since soundscapes carry even more meaning than just feedback, which is abstracted from the whole context of an environmental situation, it was assumed that it would influence participants' performance even stronger and shed a light on the purposes of the occurrence of the described effects. One of the potential explanations of the influence of feedback sounds on preferred pace is that different sound, especially ecological are inherently connected with situations were we can hear them as an effect of our actions and memories which are build in these situations. It was assumed that soundscape is a medium of richer information describing the environment and the situations in which we live. Hence, the hypothesis was that soundscape sounds will have stronger impact on the preferred walking pace than feedback sound alone. The effect of congruency between feedback and soundscape was as well a topic of interest.

Q1: *Do the various soundscape sounds affect differently preferred walking pace?*

Q2: *Are complex soundscape sounds more influential than footsteps sounds?*

Paper F (review): **"A Technological Review of the instrumented Footwear for Rehabilitation with a Focus on Parkinson's Disease Patients."**

The last paper on the topic of rhythmic walking interaction was motivated by the need of having a regular summary of foot-based technologies used in gait rehabilitation. The review concerned applications which are used and could be potentially used in gait rehabilitation and summed up requirements for the efficient foot-based gait rehabilitation system. This article serves partially as a summary of the included work on walking rhythmic interaction and opens new perspectives on research in gait rehabilitation.

Q1: *What is the stage of the foot-based gait rehabilitation systems development?*

Q2: *What are the emerging requirements for foot-based gait rehabilitation system for Parkinson's disease patients?*

Paper G and H: **"A Stationary Bike in Virtual Reality - Rhythmic Exercise and Rehabilitation"** and **"A Stationary Bike in Augmented Audio Reality."**

The second branch of the presented research was focused on a stationary bike-based rehabilitation system. Firstly, it was tested how people synchronise with music while biking with simple drum-like feedback. A thorough review on a stationary bike usage in virtual reality and rehabilitation was an inspiration to focus on designing a system for exercising, which could be easily used by e.g. elderly who are not able to go outside their homes, but still want to experience a bit of missing nature. Based on the gathered evidence, it is known that biking performance and exercise enjoyment can change as a function of VR's elements (e.g. type of display, additional music, level of immersion etc.). Therefore it was aimed to explore of the idea of introducing music and soundscape in VR. To the best of our knowledge, there is no research that tested the effect of the soundscape on exercise performance in VR. The hypothesis was that higher immersion produced by a more consistent virtual environment will be beneficial for both physical and psychological effects of VR on exercise. Our experience taught us that visual events are accompanied by auditory experience. Thus, natural sounds placed in VR can increase the perceived level of congruence and be necessary for the sense of presence. Another important aspect of each action is the auditory feedback generated by the movement. Getting not only visual but also auditory feedback of the experienced environment can increase the perceived level of control. Two forms of the feedback were chosen to be considered: (1) ecologically valid sounds, which simulate real life sounds and build soundscape and (2) a synthetic rhythmic feedback, which can help to lower variability of performance while biking.

After the discussion and consideration it was decided to focus on offering to the users only auditory feedback without artificial visual stimulation. The final concept of the design is focused on audio augmented reality were soundscape and feedback sounds will be adjusted to the users' needs and serve as a motivation for more efficient exercising. The last article describes clearly how the system will be prototyped and tested with the users. It is as well a base for future research and development. The results of the investigation should help to improve e.g. the elderly exercising and facilitate understanding of the exercises procedures and aims, provide knowledge for designing proper feedback signal and support the users with intuitive, comfortable, not stressful and even relaxing way of exercising.

Q1: *What is the stage of a stationary bike usage in virtual reality, augmented reality and rehabilitation?*

Q2: *How can we control auditory stimulation through physiological data and general users performance?*

The Experimental Methods

10 Experimental Design

In this chapter, the methods used in the research articles (papers: B, C, D, and E) are summarised. The information which summarise the ideas and content of the remaining articles are described sufficiently in the chapters III (Research Questions) and V (Discussion and Future Work). First, the experimental design utilised in each of the studies will be described followed by a specification of a technical apparatus which was common for the most of them.

Paper B

To investigate the topic of rhythmic interactive walking with ecological auditory feedback, an experiment where we compared three different interaction modes, three kinds of auditory feedback, and three tempi was designed. The three interaction modes were 1) instantaneous auditory feedback per detected step (section A), 2) pacing with a constant tempo (section B1), and 3) pacing with a tempo that adapts to the instantaneous walking pace of the subjects (section B2). In all interaction modes, auditory feedback was one of the following: I) a 1 kHz sinusoidal, II) synthetic footstep sounds on wood, and III) on gravel. The tempo was chosen among 80, 105, and 130 BPM, each beat corresponding to one step. These were chosen to be below, around, and above the typical walking pace of humans. Table no. 1 summarises experiment design.

20 participants' performance was tested in the experiment. The whole scenario consisted of 22 experimental trials, each lasted around 1 minute. In section A participants were asked to walk in their preferred tempo (4 trials) and in section B to follow tempo presented by sound (18 trials). In section A, after three takes with auditory feedback (the remaining one was salient) in a random order, the participants were asked how much they agreed with the statement, "The sound of footsteps sounded as a natural consequence

Table 1: Summary of the experiment design described in the paper B.

E#	I-MODE	FEEDBACK	TEMPO (BPM)	TASK
a1	STEP (Silent)	None	-	Walk at own pace
a2	STEP (Sonified)	Sine, wood, gravel	-	#
b1	TEMPO (Constant)	Sine, wood, gravel	80, 105, 130	Follow tempo
b2	TEMPO (Adaptive)	Sine, wood, gravel	80, 105, 130	presented by sound

of walking" on a scale of five, where 1 was strongly disagree and 5 was strongly agree. After each trail in section B, the participants were asked to what extent they agreed with the statement, "It was easy to follow the tempo" on a scale of 1 to 5 similar to the one described earlier. Additional two questionnaires consisted of the questions about the naturalness of the presented sounds, tempo preferences, and the ease in following the tempo with specific feedback were carried out after subsections B1 and B2.

The analysis of experimental data was based on information about each participant's tempo measured in beats per minute (BPM) (the tempo was recorded every time the system detected one step). The analysis was conducted based on the average tempi, the mean square error (MSE) between the given (target) and performed (measured) tempo, and the trend of tempo changes obtained from the slope of a line fitted to the measured tempo. The sign of the trend indicated deceleration or acceleration, and its value quantifies this in the experiment.

Paper C

The procedure of the following experiment which was designed to investigate the effect of additional haptic stimulation on rhythmic interactive walking was very similar to the previous experiment. The same interactive modes and types of feedback were tested. This time a haptuator was incorporated to our experimental design and only one tempo (105 BPM) was chosen to follow in section B. Again, participants were asked to walk in their preferred tempo while instantaneous haptic, audio or haptic+audio feedback were presented as a result of each step. Questionnaires were conducted as well. Overall, the experiment consisted of 28 one-minute-long trials. Table no. 2 summarises experiment design.

Paper D

Since, the EEG experiment was strongly linked with behavioural experiment no. 1 (paper B) it was decided to keep the experimental procedures as similar as possible. However, the restriction of EEG based experiments

Table 2: Summary of the experiment design described in the paper C.

E#	I-MODE	FEEDBACK	MODALITY	TASK
A1	STEP (Silent)	None	-	Walk at own pace
A2	STEP (Sonified)	Sine, wood, gravel	audio, haptic, audio and haptic	#
B1	TEMPO (Constant)	Sine, wood, gravel	audio, haptic, audio and haptic	Follow tempo presented by sound
B2	TEMPO (Adaptive)	Sine, wood, gravel	audio, haptic, audio and haptic	#

forced to test the interaction while sitting and add one more non-ecological stimuli, which in physical structure reminded of gravel sound, but was not associated with any natural sound. Due to the requirements of the several trials repetitions the focus was only on the section where participants were asked to follow presented tempo with constant pacing (paper B, section B1).

As before, the participants heard acoustic stimuli which presented separate steps performed on the chosen ground materials. Gravel (AE) and wood (SE) sound were used as ecological sounds and aggregate (AN) and solid (SN) artificial sounds as non - ecological sounds. Both artificial sounds had an acoustic structure similar to the corresponding ecological sounds, but were not associated with walking on any existing ground materials. Four different feedback sounds and three different tempi gave overall 12 different trials; each was repeated three times. Each trial consisted of 14 steps. The trials were randomised. Participants' task was to follow tempo presented by sound. After the 36 trials they were asked to fill in a questionnaire, where they stated which tempo was the easiest/hardest to follow and which type of cue made synchronising easier/more difficult. The experiment was prepared and conducted in Action and Cognition Laboratory at Adam Mickiewicz University in Poznan.

Paper E

This study describes an experiment designed to further explore the influence of footstep sounds and additional soundscapes on preferred pace of a person. In 20 trials, four auditory feedback conditions (gravel, wood, sine wave, silent), four different soundscapes (cafe, busy office, sea shore and street) separately and combined together and one silent conditions were tested. All trials were presented in randomised order. In each of the 20 trials participants were asked to walk in their own preferred pace. Table no. 3 summarises experiment design. After each trial participant were asked several questions which are specified in the list below.

Table 3: Summary of the experiment design described in the paper E.

SECTION	SOUNDSCAPE	FEEDBACK	QUANTITY
A1	seashore, busy street, cafe, busy office	gravel, wood, sine wave	12
A2	seashore, busy street, cafe, busy office	none	4
B	none	gravel, wood, sine wave	3
C	none	none	1

Q1: *Evaluate the sense of effort you experienced while walking (1 no effort - 7 high effort).*

Q2: *It was easy to walk while listening to the sounds of footsteps and soundscapes (1 very easy - 7 very hard).*

Q3: *The pace I kept while walking was: (1 very slow - 7 very fast).*

Q4: *Feedback felt as a natural consequence of walking. Consider only footsteps sounds (1 strongly disagree - 7 strongly agree).*

Q5: *Feedback felt as a natural consequence of walking. Consider footsteps sounds and soundscape (1 strongly disagree - 7 strongly agree).*

Q6: *Feedback was congruent with soundscape (1 strongly disagree - 7 strongly agree).*

Q7: *In which place do you think you were walking?/On which surface do you think you were walking?*

The analysis of experimental data was based on information about each participant's tempo measured in beats per minute (BPM) (the tempo was recorded every time the system detected one step). The analysis was conducted based on the average tempi.

11 Technical Apparatus

In the studies described in the papers B, C, and D, walking sounds were used as input. One of the advantages of using sound instead of other sensor modalities, such as sensor- or video-based tracking, is the satisfactory temporal resolution with noninvasive sensors and lower latency. The typical sampling frequency for audio is 44,100 Hz, whereas for most sensor- based devices, such as accelerometers, it is at most 100 Hz. Using sound as input for interactive applications, however, requires efficient algorithms for processing and understanding the audio to avoid latency.

The constructed system consisted of a synthesis engine for walking sounds and two different detection modules for tracking user footsteps (the principles of the synthesis engine are described in more detail in Nordahl et al. [75] and Jylhä et al. [42]). The system reproduces synthetic walking sounds by extracting the envelope of human footsteps and using it to drive a physically informed synthesis model. This setting directly synthesises a footstep sound, preserving the envelope of the user's step. In an alternative setting, human footsteps are detected as events, and the walking tempo is estimated. This information is used to control the synthesis engine by sequentially triggering a footstep sound according to the estimated tempo. In this setting, the system thus produces footsteps as a stimulus, either with a fixed tempo or with one adapting to the walker's tempo.

The footstep sounds produced by the person walking in place on a step machine were captured by a microphone (Shure BETA 911 - a high-performance condenser microphone with a tailored frequency response designed specifically for kick drums and other bass instruments). Specifically, the microphone was placed under an aerobic step. Its features make it a good candidate for capturing footstep sounds. The synthesised sounds are conveyed to the user via an open-design headphone.

A novel addition to the described setup was used in paper C. An industrial haptuator by TactileLabs, mounted on the step machine, was used to provide tactile stimulation to the participants. An important advantage of this haptuator is that it can be driven by an audio card without the need of pre-amplification. Moreover, the haptuator weights close to 250 g, and its design allows to displace the surface it is mounted on up to 10 mm. This powerful low-frequency response comes with two difficulties: (1) the vibration is usually audible, and (2) the audio input to the haptuator should contain low-frequencies. The first difficulty was alleviated by providing the auditory feedback with an in-ear headphone inside an earmuff, and the second one by estimating the envelope of the synthetic sound, which modulates the amplitude of an 100 Hz sinusoidal for driving the haptuator. Fig. 1 presents a simplified visualisation of the experimental setup.

The only study which used pre-recorded sounds was the EEG study (paper D). Due to the specifics of the EEG experiments (especially high susceptibility to interferences coming from the body movements) and available setup participants were sitting during the experiment. Their legs were placed on an aerobic stepper with the answer buttons mounted on top of it. Microcontroller Makey Makey was responsible for sending data from footsteps to SuperLab software. EEG data were collected by BioSemi software and cueing

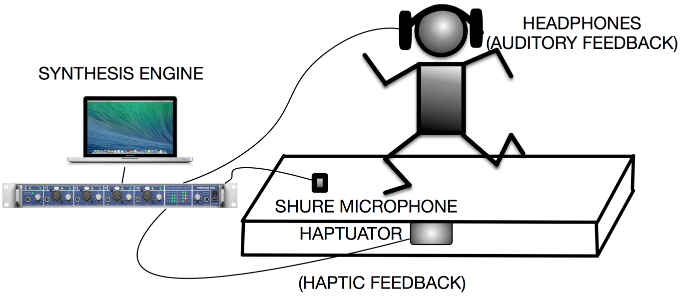

Fig. 1: A simplified visualisation of the experimental setup used in the studies described in the articles C (with haptuator), B and E (without haptuator).

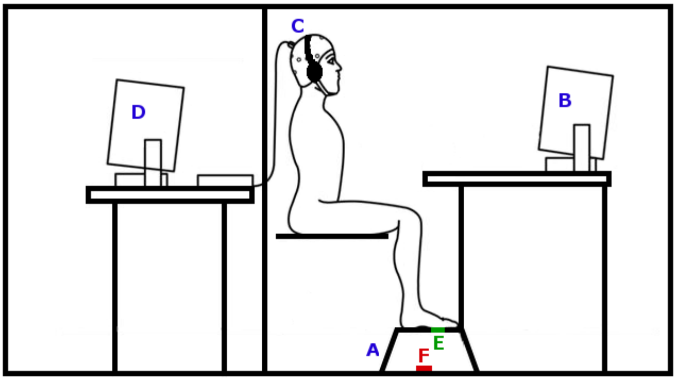

Fig. 2: A simplified visualisation of the experimental setup used in the study described in the article D. It consisted of: an aerobic stepper (A), the answers buttons (E), microcontroller Makey Makey (F), SuperLab software (B), BioSemi system (D), and headphones (C).

sounds were presented through headphones. The EEG results were continuously recorded by the Biosemi Active Two (64 - channel) and Brain Vision Analyzer was used for data analysis. Fig. 2 presents a simplified visualisation of the experimental setup.

Discussion and Future Work

12 The Summary of the Results

This thesis discusses several topics orbiting around the influence of cues, feedback and soundscape on rhythmic interaction (walking and biking). The main focus was on ecological feedback.

The research questions were evaluated in a behavioural and neurological context during rhythmic walking interaction and a concept of a bike-centred system for indoor exercising was proposed. In the previous chapters the background knowledge and research questions were presented. Here, the most interesting outcomes, the highlights of each paper were chosen to be an appetiser for the forthcoming articles and an introduction to the following discussion. Discussion section is en extract of the topics examined in the articles. It is recommended to address the papers for more extensive discussion of the results.

Paper A (Review)

- The advantages and threats of using auditory and haptic feedback were recognised.
- The methods of parameter mapping and earcons were mostly utilised.
- Feedback in all of the summarised studies were presented in a concurrent manner and transferred knowledge of performance.
- Haptic feedback was mostly utilised in walking scenarios.
- Auditory feedback was effective only in some of the included studies.

Paper B

- Different audio cues affect a person's walking rhythm, providing insight for the design of rhythmic, feet-based entertainment, or therapeutic systems.

- An advantage of using walking sounds as input is the satisfactory temporal resolution with noninvasive sensors and lower latency.
- Both ecological sounds and an adaptive tempo have an effect on desired performance.

Paper C

- Designed system detects steps and analyses users' tempo in real time.
- Our system presents in real-time ecologically valid audio and haptic feedback.
- In conditions with auditory stimulation gravel was perceived as the most natural.
- The easiest cues to follow were presented by audio+haptic and audio signals.
- Audio+haptic gravel feedback was perceived as the most natural.

Paper D

- 105 BPM tempo gave the highest activation in alpha wave-band.
- The results obtained for beta oscillations revealed a decrease in activity for ecological sounds.
- Gamma oscillations occurred to have the highest activity for both aggregate sounds.

Paper E

- Different type of soundscapes and footsteps sounds can influence preferred walking pace.
- Since soundscape convey larger amount of information about the meaning and situation it has larger impact on preferred pace than sounds of footsteps presented separately.

Paper F (Review)

- There is a need for more efficient, specialised and personalised foot-based gait rehabilitation systems for Parkinson's disease patients for everyday use.

Paper G

- As an introductory review, it shows that a stationary bike is widely used in rehabilitation and virtual reality applications.
- The potential advantages of using auditory feedback and music while indoor biking are discussed.

Paper H

- Here, a bike-centred system for more efficient and motivational exercising with a use of physiological data and pedalling rate, which control soundscapes and feedback presented to the users is proposed.

13 General Discussion and Conclusions

While performing research constituting this thesis, me and the co-authors were specifically interested in the influence of auditory and haptic ecological feedback and cues on rhythmic walking stability and perceived naturalness of feedback and synchronisation ease with presented cues. The results of the experiments showed a great potential of using ecological signals in paced-walking. It was shown that when people were asked to walk in their preferred pace, they walked the slowest with gravel feedback. Wood feedback makes them walk in medium pace and a sine-wave in the fastest [58]. To test this effect even further the soundscape sounds were added, which were congruent and incongruent with the sounds of the footsteps. The analysis showed that soundscape sounds can manipulate participants pace even more than footsteps sounds alone [57]. When people are asked to synchronise with above-mentioned rhythmic sounds their results are similar with a slight worse performance with gravel cues [59]. Even though this feedback produces the highest synchronising error it is perceived as the one, which is the easiest to follow [58]. In the same study [58], haptic modality as a way of rhythmic walking stimulation was tested. It was observed that haptic stimulation is not efficient in rhythmic cueing, but it might help to improve naturalness of walking experience. Both tasks, synchronisation and walking in the preferred tempo are rated as easier when the ecological cues or feedback are presented (especially gravel feedback). Gravel feedback was the most recognisable sound.

Seashore soundscape and gravel feedback remind mostly relaxing moments where walking pace is in general slower. The memories carried by the sounds and general indication of slow tempo (sea waves) might be a cause of an average slower pace chosen by the participants. The aggregate structure of the acoustic signal might as well cause the less lively walking pattern, as opposed to solid structure of the other sounds (wood and sine wave). The structure of a signal was partially responsible for better synchronisation with auditory cues. What is more, out of the two tested solid sounds, the ecological one caused better performance. An addition of haptic stimulation was not efficient in rhythmic cueing due to the placement of the source of vibrations. The haptuator was placed below an aerobic stepper and participants were losing contact with the vibrations while walking. The same effect should be studies with haptuators placed in the shoes. In general, supplementary haptic feedback increased the naturalness of a walking due to more congruent sensorial experience.

I believe that usage of soundscapes and feedback sounds can be used as a pace-changer in a relative manner in closed-loop scenarios. Those can be used when a person should speed up or slow down their behaviour without a need of achieving specific tempo rate. Sound cues are widely used in rehabilitation to motivate patients to walk. Ecological sounds which are already associated with everyday walking can activate stronger motivation and produce more natural rehabilitation situation. Incorporating feedback sounds into soundscapes and adding haptic feedback can heighten the perception of congruency and drive the movement action. As well, in the EEG experiment it was shown that ecological stimuli caused decrease in beta activation, which is associated with motor control [60].

14 Future Work

The very encouraging results of the behavioural studies and promising outcomes of the EEG experiment motivate me for further exploration of the topic of ecological feedback in rhythmic interaction with a special focus on walking and gait rehabilitation. If the new EEG experiments will prove similar effects, especially in beta waves it should motivate scientist and practitioners to exploit these type of feedback and cues in rhythmic walking interaction. The further studies on haptic feedback need to be done. It is planned to improve the delivery system for haptic feedback and explore the goals which tactile stimulation can help to acquire. It was observed that it is not an efficient way of rhythmic cueing, but it definitely helps in achieving more natural experience, which is necessary if we focus on ecological stimuli. Tested additional soundscape sounds as stimulating environmental context gave as well expected results of modified walking pace. As a next step here I see deeper exploration of the causes of such effects. It is planned to build more controlled soundscapes samples where rhythmic elements and amount and characteristics of sound events will be the independent variables.

The last described project is already a plan for the future. It was decided to incorporate results coming from the studies on rhythmic walking and observe if the similar effects can be observed in biking. Since biking and walking share some function and both are inherently rhythmic tasks, I believe that similar effects of affected tempo and heighten perceived ease of performance could occur.

During these three years of exciting, demanding and extensive research investigation I gained skills which are necessary to become an independent researcher and as well to work in a team and organise work according to the skills, demands and passions of the group members. I realised that research carrier requires your heart and soul and if you don not love it, you will not survive. To be more serious, I definitely learnt how demanding is experiments' preparation and how satisfying is to collect and analyse data and to discover the answers to your own scientific questions. If I had to choose, I would say that EEG study (paper D) was the most challenging one. The many questions of how brain activity is correlated with movement are still unanswered. I attempted to answer and investigate a few general questions, and even if the study had some limitations, I am still proud of the encouraging results. Through the studies which are described in papers D, C and E I definitely learnt how much patience is needed to prepare and perform your own study and how not to get drowned in the data during analysis. The very high level of organisation, planning and ordering is required to have control over each step of the study. These three years was a time of conducting own research and as well of a dissemination of the obtained results. Through writing and presenting the results at the conferences I learnt to be humble and open for other ideas and criticism, as well as to be proud of my own work. However there is still a lot to be done in this area.

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