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An investigation on the impact of auditory and haptic feedback on rhythmic walking interactions☆

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ABSTRACT

This paper presents a system capable of rhythmic walking interaction by auditory and haptic display. Likewise, it summarizes the results of the research on the influence of the audio and haptic stimulation on rhythmic walking interaction. The system detects user's footsteps and either provides interactive real-time feedback or suggests a pace using a synthetic walking sound or vibration. This pace is either a constant tempo or adapts to the walker. Auditory and haptic feedback signals are either ecological physically-based synthetic walking signals or simple sinusoidal beeps. In the experiment, the different auditory and haptic feedback and interaction modes are studied with respect to their effect on the walking tempo. The results show that participants synchronise equally well with the tempo with either audio or haptic cues, but indicate the audio–haptic conditions as the easiest to synchronise with. Moreover, results indicate that multimodal audio–haptic feedback provide the most natural feeling. These results have implications on the design of interactive entertainment or therapeutical applications.

1. Introduction

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.

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) cues helps gait performance in patients with Parkinson's disease (PD) (De Dreu et al., 2012; Thaut and Abiru 2010; McIntosh et al., 1997; Suteerawattananon et al., 2004; Roerdink et al., 2007; Thaut et al., 2007). External rhythms presented by auditory cues may improve gait characteristics (Suteerawattananon et al., 2004; Roerdink et al., 2007; Thaut et al., 2007), and can also be used to identify deficits in gait adaptability (Bank et al., 2011). However, 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 (Baram, 2013). Walking pace and step length are the characteristics of gait, which should be guided by sensory cues for gait rehabilitation. Auditory cues are efficient for pace and visual cues for step length. When performing more challenging, or secondary tasks PD patients become increasingly reliant on external cue information (Baker et al., 2007; Rochester et al., 2007). Since the cognitive mechanisms of PD patients are potentially impaired, it is worth to address only one modality while cueing. Ecological signals, defined as those stimuli which are encountered in everyday life, such as walking on different materials such as gravel or wood, have the possibility to convey richer information than only a person's pace. Based on footstep sounds, listeners can determine e.g. their gender and mood (Giordano and Bresin, 2006).

In non-clinical cases, 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 (Styns et al., 2007). Moreover, recent studies show that recurrent patterns of fluctuation affecting the binary meter strength of the music may entrain the vigour of walking movement (Leman et al., 2013).

Until now, few studies have shown the role of interactive auditory feedback produced by walkers in affecting walking pace. As an example, in Turchet et al. (2013), individuals were provided with footstep sounds simulating different surface materials, interactively generated using a sound synthesis engine (Nordahl et al., 2011), triggered by shoes embedded with pressure sensors. Results show that subjects' walking speed changed as a function of the simulated ground material. Moreover, footstep sound events have been shown to successfully convey spatio-temporal walking information to healthy participants (Young et al., 2013). Recent research

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investigating the role of music on temporal aspects in walking behaviour in an urban setting, show that music affects the walking tempo, although the beat did not lead to precise synchronization (Franěk and van Noorden, Režný, 2014). Moens et al. (2014) demonstrated that walkers can synchronize 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.

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 (Turchet et al., 2010). As a matter of fact, both auditory and haptic feedback are represented as temporal variations, which can be simulated with similar patterns, at different frequency ranges. Moreover, when exposed to audio and haptic modalities, subjects are able to best recognise different materials delivered haptically or as a combination of auditory and haptic feedback (Giordano et al., 2012).

In previous research, we investigated walking as a rhythmic action and experimentally investigated the effect of auditory feedback (Maculewicz et al., 2015) in a closed-loop interactive sonification framework (Hermann et al., 2011). Different kinds of auditory feedback were compared, including ecological feedback such as footsteps on wood and gravel as well as a non-ecological feedback such as a sinetone. Moreover, three kinds of rhythmic interactions were compared, specifically footsteps played at a constant tempo, footsteps generated interactively by the user and footsteps that adapted to the user. Results show that feedback with ecological sounds resulted in a performance comparable to sine waves, and, in the case of wood, provided a more stable tempo.

In the literature many existing systems for gait rehabilitation can be found, based on the idea of actuated shoes or floors (Hove et al., 2012; Novak and Novak, 2006; Zanotto et al., 2014; Healthcare, 2010). Moreover, commercial applications of haptic feedback in insoles are starting to appear in the market. As an example, the company Ducere[1] has recently launched some haptic footwear which enables the blind to receive directions on specific locations, provided by an app.

Our study is focused on participants' behavior rather than on hardware development, since the great part of the hardware development has already been introduced in our previous research. We are interested in further exploring the topic of rhythmic interaction, investigating additionally the contribution of haptic feedback. Specifically, we wish to understand the role of feedback's naturalness and the role of the haptic and auditory modalities in facilitating the task of keeping a specific tempo and choosing preferred one. We want to analyze if the role of audio and haptic stimulation is similar or they have their own specific roles in performing actions, which are interesting for us. Since participants are asked to perform two different tasks, we can analyze the roles of haptic and audio signals in following presented pace or choosing the preferred one. Using an ecological approach (Gaver, 1993), as done in (Maculewicz et al., 2015) we investigate how different auditory events support rhythmic actions, and whether haptic feedback combined with auditory feedback facilitates the synchronisation.

2. Experiment design

We designed an experiment to further explore three different interaction modes and the way subjects respond to them while varying feedback modality (auditory and haptic) and feedback type (gravel, wood, sine wave). We chose the same materials as in our previous study (Maculewicz et al., 2015). Sine wave, to imitate metronome-like feedback, wood—as an ecological sound, which in structure (solid) is similar to the sine wave, and gravel as an ecological sound with different structure (aggregate). To investigate how these conditions affected rhythmic behaviour, we divided our experiment in four parts. Each part consisted of a walking in place task and questionnaires. A summary of the experimental design is presented in Table 1 and a video describing experimental conditions can be found here[2].

2.1. Step-wise interaction

In parts A1 and A2, participants were asked to walk 60 steps for each trial; the conductor of the experiment informed participants when to stop and finish each trial. Since participants' preferred pace varied across the group they were asked to walk fixed amount of steps in each trial in parts A1 and A2. Part A1 had one condition—no auditory feedback and part A2 had three conditions (1) only-auditory feedback, (2) only-haptic feedback and (3) auditory and haptic feedback. After each of the randomized ten trials (three modality modes multiplied by three types of feedback plus one silent trial), the participants were asked how much they agreed with the statement: "Feedback felt as a natural consequence of walking" on a scale of five, where 1 was strongly disagree and 5 was strongly agree.

2.2. Modality-wise interaction

The second part of the experiment was divided into two sessions (B1 and B2). Each session consisted of nine 40-s trials. In these sections tempo-wise performance was much less differentiated than in previous two. We decided to keep these trials 40 s long since these time was approximately equivalent to 60 steps done in 105 BPM pace. In both sessions, the participants had the same task: follow the tempo presented by auditory or haptic cues, which were presented separately or simultaneously. The tempo presented in B1 was constant, but in B2 it adaptively adjusted to the participant's detected tempo, which could influence the decrease or increase in the participant's tempo. The adaptation was limited to $\pm 1\%$ percent of the instantaneous tempo, which was considered undetectable by humans in the range we were interested in. For all test cases, the sounds of walking were recorded, along with a log of time stamps for each detected step as well as the continuously updated tempo estimate. Online tempo estimates were computed from the moving average of six previous onset-to-onset interval values. After each session in parts B1 and B2, the participants were asked to what extent they agreed with the statement that" It was easy to follow the tempo" on a scale of 1 to 5 similar to the one described earlier.

2.3. Types of feedback

In the experiment we used three types of auditory feedback with corresponding haptic feedback. Haptic and auditory modalities were stimulated separately or simultaneously. We obtained nine trials in parts A2, B1, and B2 by combing three different types of feedback (gravel, wood, sine wave) and three modalities (only-audio, only-haptic, audio and haptic). The one trial in A1 was without any feedback. The tempo that participants followed was equal to 105 BPM. We chose this tempo based on our previous results, since participants indicated 105 BPM as the tempo

[1] http://www.duceretech.com/.

[2] https://vimeo.com/132429374.