A Wearable, Customizable, and Automated Auditory Cueing System to Stimulate Gait in Parkinson's

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ABSTRACT

Gait impairments often hinder the mobility of people living with Parkinson's. Even though effective therapeutic options exist, with time, progression of the condition is likely to restrict their effect. Auditory cueing has been used as an alternative to improve the gait of people living with Parkinson's, however, existing solutions offer limited customization options, which restricts their efficacy in everyday life. This paper presents a wearable, customizable, and automated system that stimulates gait using rhythmic cues. Besides offering personalization of the type of stimuli, the system enables customization of temporal parameters of walking, such as cadence and swing/stance duration. The developed system uses off-the-shelf equipment and can be tailored to the needs of the patient.

Figure 1: Patient wearing the auditory cueing system.

CCS CONCEPTS

• **Applied computing** → **Health informatics**; • **Human-centered computing** → *Mobile devices*;

KEYWORDS

Parkinson's disease, gait impairments, rhythmic stimulation, auditory cueing, headset, smartphone, sound synthesis

1 INTRODUCTION

Parkinson's Disease (PD) is a progressive neurological condition characterized by motor and non-motor symptoms [15]. Despite the advances in pharmacological and surgical techniques, gait and balance problems persist, which challenge patients' ability to safely walk or exercise [22, 23]. Moreover, the progression of the condition can worsen the response to medication, leading, for example, to freezing of gait (FoG), a particularly debilitating feature of the disease [17].

Patients with PD tend to exhibit shorter step length and, to compensate, increase their step frequency [30]. These symptoms are usually referred to as *continuous gait problems*, as the changes in the walking pattern are more or less consistent from one step to the next [11]. With disease progression, *episodic gait disturbances* such as FoG can also appear. FoG is characterized by a sudden loss of movement that occurs while walking or when trying to initiate gait. Festination episodes, characterized by small and rapid steps, can also occur, which frequently leads to falls [10].

To reduce the impact of the disease on mobility, external rhythmic stimuli [1] can be applied. In particular, stimulation in the form of sounds, referred to as auditory cueing, has a significant impact in the movement, helping to overcome gait impairments [1, 11].

When patients hear rhythmic sounds, they involuntarily try to synchronize the rhythm of their steps with the rate of the sounds. Auditory cueing can thus motivate patients to walk with the most appropriate cadence, leading to improvements in gait quality. Multiple studies have found a positive

[1] Recent work has also suggested using visual cues, projected on the floor [8], or appearing on Google glass [36], yet the evidence for auditory cueing is currently stronger.

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impact of the rhythmic sounds on step length [16, 21, 26], walking speed [3, 12, 16, 32], gait variability [3, 11] and FoG episodes [1, 31, 35].

However, and while auditory cueing is simple, effective, and free from side-effects, current solutions lack personalization options. In addition, they are affected by the lack novelty effect due to stimuli repetition [5, 35].

To address some of these limitations, an automatic, versatile and configurable Auditory Cueing System (ACS) has been developed to fit patient needs and tackle motor symptoms in PD. Our prototype uses a smartphone and a headset available on the market, being able to provide cueing automatically (Figure 1). It can be personalized to the user, by selecting an appropriate type of stimuli (including music) or fitting synthesized sounds to the characteristics of the gait of each patient.

2 RELATED WORK

Sound is commonly used to convey information to the users. Temporal characteristics of sound, in particular, can be intuitively associated to rhythmic tasks, as is the case of walking [9]. Besides rhythm, other sound properties such as pitch can be used to specify other gait properties, which can be explored in benefit of patients with PD [29].

Recorded sounds of gravel footsteps, for instance, can be easily associated to the stance phase of walking, and, therefore, lead to an adjustment of step duration and length in people with PD [29]. In an attempt to directly provide feedback on step length, Rodger et al. [29] applied sounds during the swing phase of walking, which led to a reduction in step length variability.

More complex sounds, such as music, can influence other elements of movement. Music, like movement, is multidimensional, hence it can be naturally linked to spatial, temporal, and force elements of the movement [2, 14, 33]. Moreover, music bypasses the areas of the brain affected by the disease and is able to access healthy ones, influencing the organization of movement in time and space [25]. Benoit et al. [4] demonstrated that after a 1-month gait training with a familiar German folk song the stride length increased.

The metronome is a device typically used by musicians as a reference to help keeping a steady tempo. It also allows people with PD to predict when the next step should occur, facilitating movement optimization and execution [4]. Multiple authors reported the benefits of the metronome on the gait of patients with Parkinson's, however, some studies show negative aspects as well. According to Hunt et al. [13], walking in time to a fixed rhythm like the one provided by the metronome changes the natural dynamics of the human gait. Moreover, Morris et al. [20], argue that temporal cueing strategies like the metronome are limited in its effect, due to the lack of spatial feedback.

Table 1: Characteristics of actuators in PD (*M – Metronome, E – External device, S – Smartphone*).

Name	*Cueing Trigger*	*Sound*	*Sensors*	*Device*
GAITAID [19]	Manual	M	–	E
CuePack [28]	Manual	M	–	E
CuPiD [6]	FoG	M	2(ankles)	S
REMPARK [27]	FoG, Slow mov.	M	1(waist)	S
BeatsMedical [18]	Manual	M	–	S

While considerable prior work in auditory cueing exists, few solutions made it to the market (see Table 1 for a summary of available solutions). Some solutions are limited because they depend on operators to trigger cues. Yet, all solutions are limited to the use of the metronome as a strategy for cueing. In addition to the limited effects they may offer, overly simplistic sounds such as the metronome can become monotonous after prolonged use [5]. Alternative types of auditory stimulation – for example, sound synthesis and (rhythm-matched) music – are currently not supported. Moreover, existing solutions offer limited customization options, which hinders the potential of sounds to offer a personalized strategy for cueing.

3 DEVELOPED SOLUTION

We developed a wearable, customizable, and automated Auditory Cueing System (ACS) to stimulate gait in PD (Figure 1). An off-the-shelf Android smartphone was used to generate and manipulate auditory cues and stream them via Bluetooth to a commercial headset.

Audio is generated and manipulated programmatically, enabling a higher control over sound characteristics and a better fit to the required feedback. The ACS was integrated with a sensor-based gait analysis and symptoms detection sub-system (commercialized by Sense4Care[2]), which was responsible for triggering the cueing system.

Cueing Strategies

Personalization and versatility were considered key aspects of the solution. Thus, four different types of cueing sounds were developed and/or manipulated in Pure Data[3], resulting in the development of four different modules: metronome, stance sonification, swing sonification, and music.

Metronome. Metronome beats were generated in Pure Data resorting to a pure cosine wave oscillator (Figure 2). Signals were modulated to play during a short part of the whole

[2]http://www.sense4care.com/parkinson/
[3]Pure Data is an open source visual programming language that is typically used to process and generate sound, video and graphics. The software is available at https://puredata.info

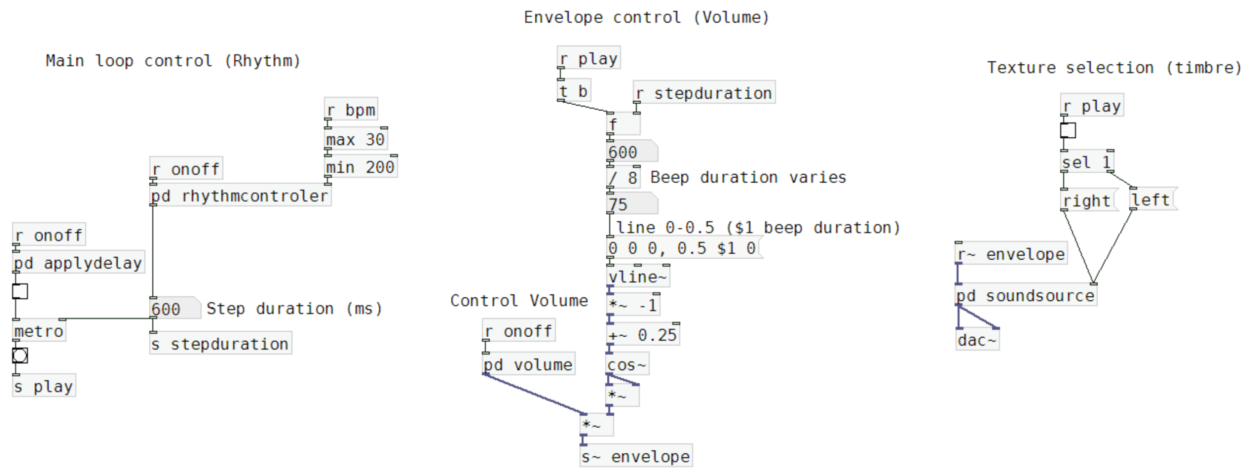

Figure 2: Pure Data patch example.

step duration time-frame, therefore providing feedback to the expected timing of the heel-contacts while walking. The number of beats per minute (BPM) is adjustable to influence the rhythm and, indirectly, the length of the steps [3], therefore being capable of fitting each patient's needs.

Stance Sonification. The sound of walking on gravel is composed by the sounds of stones of different dimensions produced while the foot is in its stance phase of walking [34]. An existing gravel texture sound synthesis program (taken from [24]) was used to produce the desired texture. On top of it, a modulator was applied to mimic the interactions of the foot with the ground: first, the heel contacts the ground; secondly, the weight is slowly transferred from the heel towards the ball and lastly, the heel completely leaves the ground and only the ball supports the weight [7, 24]. Three half cycles of a cosine were time shifted and mixed to create this three stage envelope. By using this approach, modulator parameters of auditory cueing (i.e. the relative time spent in each of the three phases of stance) can be adjusted for a higher control over spatial and temporal parameters of gait.

Swing Sonification. The swing sonification module implements a method to sonify the "silent" part of the movement, i.e. when the foot is not in contact with the ground. For that purpose, subtractive synthesis techniques were applied starting with white noise. A low-pass filter with variable cut-off frequency was implemented and, in parallel, a sine wave tone with much lower volume was produced. The frequencies of both components were designed to depend on the swing phase duration, therefore adapting to the specific properties of each patient's gait.

Music. A Pure Data patch was produced to enable music rhythm manipulation in real time. The used algorithm was heavily based on a phase vocoder example provided by Pure Data, enabling the adjustment of music playback speed without changing music pitch. By manipulating rhythm, music can adapt to the needs of the patients. Different songs can be chosen as a stimuli, which adds diversity while being capable of adjusting to the individual preferences of patients.

4 CONCLUSION AND FUTURE WORK

A wearable, customizable, and versatile solution for gait stimulation in PD has been developed. The solution relies on off-the-shelf technology and can be tailored to the needs of each specific patient by selecting the most appropriate stimuli – metronome, music, swing sonification and stance sonification – and fitting sounds to the characteristics of the gait of each patient.

For future work, we will conduct laboratory and ambulatory tests to assess the effects of auditory stimuli on patient's gait, as well as technology acceptance and impact on quality of life. We expect this automated stimulation device to be a valuable solution to tackle motor symptoms in PD.

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