Interactive Sonification of Gait: Realtime BioFeedback for People with Parkinson's Disease

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ABSTRACT

Parkinson's disease (PD) is a progressive neurological illness characterized by the death of dopaminergic neurons in the basal ganglia. One of the debilitating aspects of the disease is the inability to generate and maintain internal cues to initiate and drive movement, particularly in complex tasks such as walking. Although dopaminergic drug treatments may improve some features of gait, they eventually become ineffective and do not address fundamental gait disturbance issues. Therefore, temporal parameters of gait are left significantly abnormal despite drug treatment. Sonification represents a novel approach to developing individualized auditory cues based on gait specific motion analysis data. We propose to use lightweight sensors that allow three-dimensional tracking of walking with real-time streaming to a mobile device for individualized sonification/biofeedback of gait. Initial results testing if people with PD are capable of recognizing and correcting distortion cues in pre-recorded music are promising, and are detailed in this paper.

1. INTRODUCTION TO PD AND MOVEMENT

Parkinson's disease (PD) is a progressive neurological illness characterized by the death of dopaminergic neurons in the basal ganglia. Because the basal ganglia is an important control center for movement, its degeneration leads to debilitating motor deficits, with gait disturbances being one of the most common. The motor symptoms of the disease cannot be eliminated and are typically managed with dopaminergic drugs. Although these treatments may improve some features of gait, temporal parameters of walking are left significantly abnormal despite medication, and asymmetrical walking, as well as episodes of freezing of gait and falling persist [1]. Pharmaceuticals eventually become ineffective and do not address what fundamentally underlies these gait disturbances—the inability to generate and maintain internal cues to initiate and drive movement.

Since medication has proven to become progressively less effective in treating problems with mobility for people with PD, therapies have developed that use external signals to help initiate and maintain movement in persons with PD including cues in the visual, auditory and proprioception domains. Rhythm, which organizes time into discrete and regular units, has been shown to be the component of music that most significantly impacts gait in PD. Therapies that use external cues to help initiate and maintain movement are promising, and music therapy in particular seems to address temporal disturbances effectively [2][3][4]. Imaging studies provide evidence that sound provokes the simultaneous activation of both auditory and motor areas in the brain, and functional MRI studies conducted in healthy individuals have demonstrated activation of the basal ganglia in response to isolated metric rhythms, particularly when the rhythm is not strongly suggested by external cues [5]. Communication between the basal ganglia and cortical motor areas, such as the premotor and supplementary motor areas, has also been shown to be more active while listening to a rhythm [6]. This is suggestive of the basal ganglia's role as an internal "clock" and its importance in rhythmic movements such as walking.

Parkinson's disease patients' difficulty in self-initiating movement, demonstrated in various imaging studies [7][8][9], can likely be attributed to the impairment of the basal ganglia as internal rhythm generators. It has been shown that participants with PD who were in the early stages of the disease, when neuronal death tends to occur only within the basal ganglia, performed significantly worse than control subjects in differentiating between a regular, rhythmic beat and an irregular beat [6]. Studies have also shown that movements in response to external cues are not impaired in PD [10], and so it may be that the impairment in beat perception does not interfere with the benefits of the therapy.

2. MUSIC & DISTORTION AS EXTERNAL CUES

Research has shown that sound is more strongly tied to temporal processing than other modalities, and therefore external auditory cues are more effective than visual cues in improving gait. This may be due to sound's stronger ability to enhance cortico-motor connectivity and/or recruit other compensatory areas such as the cerebellum. It is important to note that the general auditory deficits see in PD has not been show to override the significance of auditory-motor coupling in improving gait.

Though natural, internal cueing of movement timing is disturbed by malfunctioning basal ganglia–cortical circuitry in people with PD, an external auditory cue in the form of metronome pulses or rhythmic music can enable affected individuals to initiate steps and maintain gait movements [11][12]. In music with a clear beat, the steady temporal input serves as a continuous reference, creating a rhythmic template that influences the motor system's ability to coordinate and execute movement [13]. As the pattern of regular external cues generates temporal expectations, the temporal-motor system begins to act on those expectations, predicting subsequent beats and priming movement in anticipation of them [11][13]. In the absence of a healthy basal ganglia timing system, the cerebellar–thalamic–cortical network seems to be recruited to mediate the entrainment process, or synchronization of movement to sound (Raglio, 2015; Thaut, 2008; Benoit, Dalla Bella, Farrugia, Obrig, Mainka and Kotz, 2014; Nombela, 2013). Music cueing through the neurologic music therapy technique known as Rhythmic Auditory Stimulation (RAS) has been shown to help normalize multiple gait parameters including velocity, cadence and stride length (Arias & Cudeiro, 2010; McIntosh, 1997; Thaut, McIntosh, Rice, Miller, Rathbun & Brault, 1997).

Although the temporal aspect of music has been extensively studied, it is unknown whether more complex cues, such as combinations of rhythm and pitch distortions correlating to gait errors, could be useful for gait improvement. The purpose of our work is to investigate whether PD patients can perceive complex auditory cues, which we presented as distortions superimposed on commercial music, and utilize them for meaningful error correction.

3. PILOT STUDY – SIMULATED ENVIRONMENT

We experimented with various types of music (Jazz, Bluegrass, Classical, Pop, Rock, Electronic, Country) and distortions to determine if certain combinations would result in more effective external audio cues for gait dysfunction. To maximize distinction between sounds, we used three types of distortion: 1) **Rhythmic Distortion** that creates a jittery, shuddering sound sometimes known as "beat repeat" or "slap-back echo;" 2) **Timbral Distortion** that creates a high-frequency whooshing or warbling sound, using a frequency shifter; and 3) **White Noise** which introduces white noise, or static, to mask the sound of the music during playback. By overlaying these distortions on three commercial music pieces we created an original auditory biofeedback method that could be used with gait specific motion analysis data.

In experiment 1, we examined whether people with PD could perceive and correct audio distortions on pre-existing music. Twenty individuals with PD (12 male, aged 52-79 years, $\bar{x} = 67$ years) and fifteen healthy peers (7 male, aged 51-89 years, $\bar{x} = 66$ years) volunteered to participate in this study. All participants with PD were tested at his or her preferred time of day to take into account medication ON/OFF fluctuations. Using an iPad with a custom-designed Lemur interface [15] as the control surface (see Figure 1) we asked participants to:

1) Choose the kind of music they wanted to listen to
2) Press play, and adjust the volume if needed
3) Listen to the music undistorted for as long as they needed to get a sense of the original music prior to starting an experimental trial.

For each trial subjects manipulated a slide bar which corresponded to a randomly generated 120 point distortion curve with only one 'zero point' representing the undistorted song. Any number away from zero was recorded as error. Each participant performed three trials for each distortion on each song to complete 27 trials presented in a random order. Data was analyzed with a 3 (song) by 3 (distortion) by 2 (group) repeated measures ANOVA. Significance was set at $p<0.05$. Paired t-tests were used to measure multiple comparison effects using a Bonferroni correction. Variances were assumed to be equal unless the Levene test was violated.

We measured how long they listened to the undistorted song, how long it took for them to choose the point where the sound quality matched the original, and the accuracy of the point where they chose to stop.

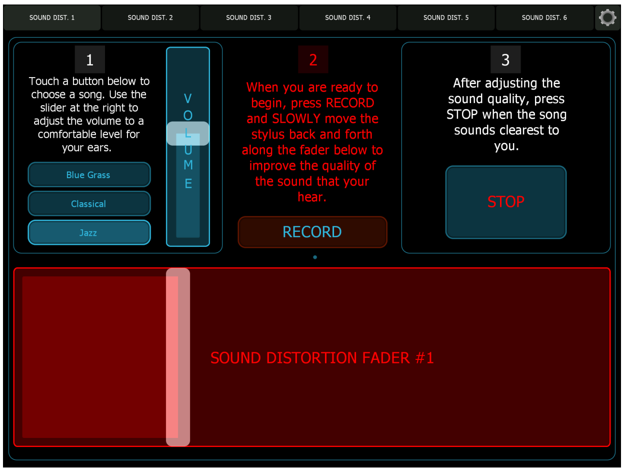

Figure 1. *Our iPAD interface designed in the Lemur App*

The Lemur application sent wireless OSC data to Max/MSP [16][17]. Our program in Max recorded the timing information, transformed some of the incoming data, and sent control data to Ableton Live [18] for playback. All the songs were stored in an Ableton Live session, and the distortions we used were bundled with the original software. In addition to the distortions, we had an extra track of generated white noise that we could fade in over the top of the original signal.

We used the "sound distortion fader" on the iPad to control a breakpoint function in Max. The slider on the iPad sent values of 0-120—this correlated to the X-axis on a function in Max [19]. We randomly created functions with six breakpoints (see Figure 2). We programmed the function so that only one of the points could to be zero on the Y-axis. This point had to between 10 and 90 on the X-axis, and this was the only point that correlated to zero distortion in the Ableton Live playback. After initial testing we also determined that we needed to ensure that none of the other randomly generated numbers were less than 10, making the single point of sonic clarity more obvious. As the subject moved the slider on the iPad, there were several areas that had less distortion, but only a single point of complete clarity.

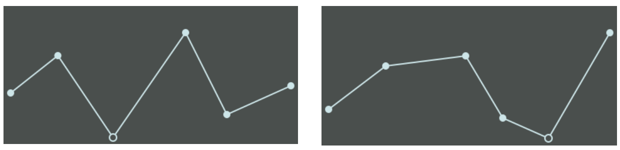

Figure 2. *Randomly Generated Breakpoint Functions with one zero point on the Y-axis—represented by the open circle*

Figure 3 shows the data we recorded from one subject's interaction with the iPad. The X-axis is time in seconds. The Y-axis is amount of distortion (0-120) where zero is no distortion and 120 is maximum distortion. The figure shows that although the subject located the zero point at 42 seconds, they continued to experiment with the sound, trying several positions before returning to the initial zero point and stopping the trial.

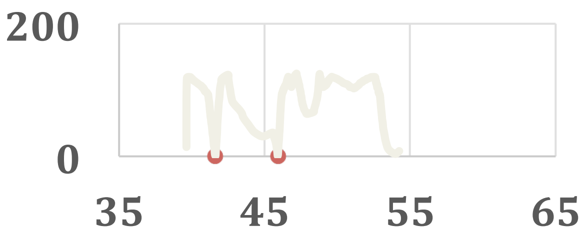

Figure 3. *Recorded Data collected in Max from iPad interaction*

With this research we were able to show that that patients with neural degeneration from PD can perceive sound distortions and utilize the information for meaningful error correction in a simulated environment with a similar speed and accuracy as their healthy peers ($p>0.05$ across conditions). However, we did find an interaction effect such that individuals with PD made more errors than control subjects when correcting distortion 1 for songs 1 ($p<0.005$) and 3 ($p<0.001$) and distortion 3 for song 3 ($p<0.05$) (See Figure 4.) Although this suggests that certain distortions presented more of a challenge to the participants with PD, it should be noted that the total error was always less than 20% of the distortion curve. This means that even the most inaccurate subject was able to minimize the distortion from a possible 120 point maximum to within 22 points of zero. For the purposes of biofeedback in gait, this represents a significant change in behavior. Our next step in a simulated environment is to present subjects with multiple simultaneous distortions to determine if it is possible to correct for concurrent auditory effects.

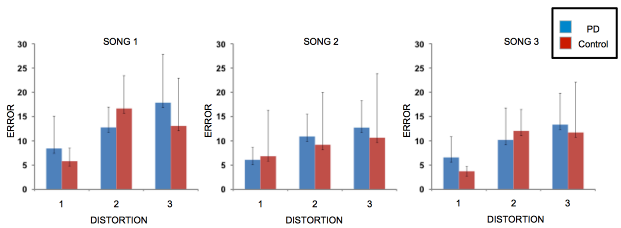

Figure 4. PD vs. Control in Songs 1-3

4. MOVING FORWARD

Besides its innate temporal nature, music is advantageous for mobility therapy because it is pleasurable and can make treatment less stressful [20], and sound elicits quick reaction times compared to other sensory cues [21]. This is especially useful in providing seemingly instantaneous feedback so that the patient can adjust and correct their movement, as soon as they receive the external sound cue that indicates the need for correction. Since gait is less automated in PD, it relies more heavily on cognitive attention, and diverted attention contributes to greater gait impairment and falls in Parkinson's disease patients [21]. Therefore, we are working on a system which signifies when and how the patient's gait has been disturbed, to improve a patient's gait as well as prevent future falls.

Presently there is no commercially available, appropriately designed tool that can collect gait data, analyze it in real time and return the data as feedback to the individual while they are walking. In an effort to provide a personal sonification biofeedback gait improvement system, we are developing a novel sensor system that will allow three-dimensional tracking of walking with real-time streaming of gait data to a mobile device that provides biofeedback through sonification. This system is lightweight so that a person's gait is not disturbed while wearing the sensors, and it has an extended battery life so that there is no need to charge during a typical day. Our system is engineered to be compatible with commonly used mobile technology.

We are currently working on feature extraction from the data sent by the sensors. Eventually we hope to have four variables which correlate to spatiotemporal aspects of gait including speed and symmetry. This data can then be used to create distortions for the user and generate motor learning through error feedback. Rather than using sound to identify relevant biological signals, we engage the patient's perceptual system by introducing musical error that is intimately linked to deviations in gait. This biofeedback sonification system is also beneficial because it allows the patient to have agency in the development of their therapy. The individual can choose their music and develop their own routine to keep up with their therapy on their own terms. In addition, several studies show a higher activation of corticomotor areas when patients can choose what music or sounds they want to hear as external audio cues [19]. Therefore, individualization of music therapy, such the use of patient-preferred music, is more likely to engage the patient and be a more effective therapy. The goal is to create a personalized training device that leads to long-term improvement in walking for individuals with PD.

5. CONCLUSION

In laboratory experiments, highly accurate motion analysis systems are used for data capture and analysis but these systems are rarely seen in clinics and they are therefore incompatible with long-term use by patients in the home or community. More simplistic systems, like pressure-sensitive insoles, have been used to provide step-to-step measures of gait, but these systems are less accurate and have poor durability. Recently, laboratories and private companies have turned to accelerometry or devices equipped with an accelerometer, gyroscope, and/or magnometer to capture larger data sets with greater accuracy. However, even these systems lack the ability to stream the data in real-time to a second unit to create a biofeedback system. Furthermore, none of these systems leverage the power of music to motivate patients to persevere in their therapy.

Beyond the obvious implications for accessibility, biofeedback from interactive sonification results in a dynamic and descriptive portrayal of physiological events, and offers users the possibility to control and change movement and behavior the moment that a gait pathology is perceived. PD is a devastating disease that is increasingly common as people live longer; impaired gait is a particularly troublesome symptom in PD because it is a predictor of unemployment, increased burden of care, nursing home placement, falls, morbidity and mortality [23]. Effective treatment of gait impairments can improve quality of life and decrease healthcare costs. External cueing is an established means of improving walking, but an efficient, engaging cueing system does not currently exist. We believe that our technology, which uses pre-existing music as a motivator with distortion as an indicator of gait impairment, instead of systems which create sound from sensors [24], offers a powerful tool in the treatment of movement disorders associated with PD.

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