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Auditory observation of stepping actions can cue both spatial and temporal components of gait in Parkinson's disease patients

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ABSTRACT

Objectives: A common behavioural symptom of Parkinson's disease (PD) is reduced step length (SL). Whilst sensory cueing strategies can be effective in increasing SL and reducing gait variability, current cueing strategies conveying spatial or temporal information are generally confined to the use of either visual or auditory cue modalities, respectively. We describe a novel cueing strategy using ecologically-valid 'action-related' sounds (footsteps on gravel) that convey both spatial and temporal parameters of a specific action within a single cue.
Methods: The current study used a real-time imitation task to examine whether PD affects the ability to re-enact changes in spatial characteristics of stepping actions, based solely on auditory information. In a second experimental session, these procedures were repeated using synthesized sounds derived from recordings of the kinetic interactions between the foot and walking surface. A third experimental session examined whether adaptations observed when participants walked to action-sounds were preserved when participants imagined either real recorded or synthesized sounds.
Results: Whilst healthy control participants were able to re-enact significant changes in SL in all cue conditions, these adaptations, in conjunction with reduced variability of SL were only observed in the PD group when walking to, or imagining the recorded sounds.
Conclusions: The findings show that while recordings of stepping sounds convey action information to allow PD patients to re-enact and imagine spatial characteristics of gait, synthesis of sounds purely from gait kinetics is insufficient to evoke similar changes in behaviour, perhaps indicating that PD patients have a higher threshold to cue sensorimotor resonant responses.
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1. Introduction

1.1. Background

Despite optimal pharmacological treatment, gait disturbances are a common feature of Parkinson's disease (PD), the most prevalent being significant reductions in step length (SL) (Morris, Iansek, Matyas, & Summers, 1996). Such gait impairments are due to the progressive degeneration of dopaminergic cells in the basal ganglia that are associated with ideopathic PD (Jankovic & Tolosa, 2007). The basal ganglia are responsible for the habitual and automatic control of movement planning, initiation and movement scaling (Asmus, Huber, Gasser, & Schols, 2008; Robertson & Flowers, 1990). Therefore, when PD patients perform habitual movements, such as walking, impaired excitatory output from the basal ganglia can lead to problems with movement initiation (akinesia), slowness of movement (bradykinesia) and reduced movement amplitude (hypokinesia).

A well-documented feature of idiopathic PD is the distinction between the way in which the disease will compromise habitual movement control processes, yet, neural networks involved in goal-directed and externally paced movements are relatively preserved (Redgrave et al., 2010; Torres, Heilman, & Poizner, 2011). This distinction is founded on studies showing that when relevant sensory information is available for PD patients to 'follow', improvements in motor performance are observed (Rubinstein, Giladi, & Hausdorff, 2002); a phenomenon known as '*kinesia paradoxica*'. Hence, it is assumed that the neural processes involved in goal-directed action are fundamentally different from those relating to the habitual control of movement. Furthermore, motor actions that are intended to conform to some source of external sensory information (be it visual or auditory) are thought to invoke neural networks that effectively bypass the affected basal ganglia, in order to drive activity in cortical structures. For example, the use of visual cues (placing horizontal lines on the floor) is a common technique used to enhance gait parameters, such as SL, in PD patients. Indeed, the use of this technique is

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associated with altered patterns of neural activity, most specifically enhanced activity in the lateral premotor cortex (Hanakawa, Fukuyama, Katsumi, Honda, & Shibasaki, 1999).

The concept of 'cueing' relates to the provision of sensory information that, in general, can be categorized as specifying either: (i) spatial information that informs the user of where their actions should be guided (such as lines on the floor), and (ii) temporal cues that provide information about movement timing (such as a metronome). The benefits of using visual and acoustic cues (either separately, or in conjunction with each other) are well-documented (Rubinstein et al., 2002). However, it is widely suggested that the most important aspect of gait that should be addressed through cueing strategies relates to spatial aspects, such as SL (Rubenstein et al., 2002). Traditional cueing strategies designed to convey spatial information for gait are generally confined to the use of visual cues, such as lines on the floor. However, when walking, people need to visually search various aspects of their intended walking path for successful navigation (Patla & Vickers, 1997). As such, visual cueing strategies for PD will inevitably impose numerous impracticalities for use in daily life.

Previous studies have explored the potential of using alternative cueing tools such as attentional strategies; cueing gait by verbally instructing patients to adapt SL (Baker, Rochester, & Nieuwboer, 2007; Canning, 2005). Although such work has reported significant benefits, it has also been suggested that attentional cueing alone can be problematic. For instance, it has been shown that when performing more challenging, or secondary tasks PD patients become increasingly reliant on external cue information (Baker et al., 2007; Rochester et al., 2007). Furthermore the use of attentional strategies is limited because they are internally generated and often reliant on potentially impaired cognitive mechanisms (Rochester et al., 2004; Yogev et al., 2005). These possible limitations of using attentional strategies highlight the importance of developing and scrutinising new types of external sensory guides that could ultimately provide more robust functional benefits for people with PD.

Aside from the use of attentional strategies described above, both spatial and temporal information is usually conveyed separately through either visual or auditory modalities, respectively (Rubinstein et al., 2002). Efforts to develop acoustic cues that can convey spatial information may have been discouraged by the reported detrimental influence of concurrently walking and listening to music (Brown, de Bruin, Doan, Suchowersky, & Hu, 2009). Apart from conveying temporal information, musical sounds have very little relevance to a desired action that listeners are trying to produce. Conversely, ecologically-valid 'action-related' sounds have the potential to circumnavigate these problems by inherently conveying both spatial and temporal parameters of a specific action (Gaver, 1993). In doing so, the dynamic content of the sound becomes relevant to the performance of that action, thus increasing the saliency of the sensory information.

1.2. Perceiving actions through sound

From an ecological perspective, the perception of a given action is directly mediated by the dynamics of the sensory information afforded by the observation of that action (Gibson, 1979). As such, with respect to auditory perception of action, alterations in the dynamic characteristics of a sound will afford changes in the parameters of the observed action. The processes involved in associating sounds with actions are learned at an early stage in childhood, as even young children can match environmental sounds to appropriate actions and events (Julie, Jacko & Rosenthal, 1997).

Empirical evidence has shown that listeners can not only distinguish stepping frequency from the sound of footsteps, but also determine a walker's gender and mood (Giordano & Bresin, 2006). When walking on a compliant surface like gravel, forces exerted by the foot produce seismic vibrations in the walking surface, the nature of which depends on the walker's gait parameters. For example, producing a longer SL requires greater forces being exerted by the foot, especially during the early and late stages of stance (Varraine, Bonnard, & Pailhous, 2000). Consequently, gravel particles under the foot will collide with greater force and frequency, thus increasing the resultant sound intensity, as well as other auditory parameters of the sound event (Visell et al., 2009). Therefore, according to physical laws, information relating to SL and stepping frequency can both be conveyed within a single continuous auditory display; the sound of footsteps (Young, Rodger, & Craig, 2013).

We have previously shown that during a real-time imitation task young adults are able to adapt both the spatial and temporal parameters of their own walking in accordance with the information conveyed in the sound of footsteps on a gravel surface (Young et al., 2013). The purpose of the current series of experimental sessions was to investigate whether ecologically-valid sounds can be used as an external source of sensory information for guiding walking actions in patients with PD. In Section 2, recordings of gravel footsteps were presented to patients as spatial-temporal cues for walking. Answering this question will have clear functional applications for using 'action-sounds' as sensory cues and could carry logistical benefits for users who could avail of the sounds through portable personal stereo devices.

If PD and control participants are both able to perceive and re-enact spatial and temporal parameters of stepping actions through sound, this leads to two key questions. First, can the key parameters of the action sound that specify spatial-temporal information be identified and synthesised for effective cueing? Second, in terms of the practicalities of using action-related cues, rather than concurrently walking and listening to the sound cue, could participants derive the same benefits by imagining the sound whilst walking? These questions are addressed in Sections 3 and 4, respectively.

2. Session 1

2.1. Introduction

Section 2 examined the efficacy of using real recorded footstep sounds as a sensory cueing strategy to improve gait parameters in people with PD and then compared these adaptations to those found when using an attentional strategy accompanied with a metronome. Previous work has suggested that dividing attention between two separate cues (such as a verbal instructional cue and metronome) will increase the attentional demands of the task, and potentially compromise performance (O'Shea, Morris, & Iansek, 2002). Therefore, we included a third cueing condition comprising an attentional strategy only with no metronome. Finally, the extent to which PD patients could perceive SL within the footstep sounds was controlled for through the inclusion of a fourth cueing condition where the SL represented in each of the footstep sounds was verbally clarified to the participant prior to the start of each trial.

Due to the saliency of the spatio-temporal information inherently specified within the footstep sounds, we predict that PD patients and healthy controls will be able to perceive both spatial and temporal information from the footstep sounds and adapt the respective parameters of their gait. We also predict that the magnitude of these adaptations will be comparable to those shown when using alternative cueing strategies (metronome and/or attentional strategies) previously shown to be effective in PD (Baker et al., 2007; Rubenstein et al., 2002). Furthermore, when walking to the footstep sounds, we expect that the magnitude of these adaptations to gait will be comparable between PD and control groups,

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