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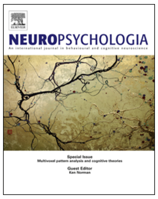

Auditory observation of stepping actions can cue both spatial and temporal components of gait in Parkinson's disease patients

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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.

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 reenact 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, thus suggesting that the processes involved in perceiving actions through sound are not significantly affected by PD.

2.2. Methods

2.2.1. Participants

A total of twenty participants provided written and informed consent to take part in the current study. Ten participants (4 male/6 female) had a diagnosis of idiopathic PD and a non-fluctuating response to Levodopa (PD group). Within the control group (4 male/6 female), participants had no known neurological impairment. Within both groups, no participants had any cognitive ($<26/30$ in the Mini Mental State Examination (Folstein, Folstein, & McHugh, 1975)), or self-reported auditory, musculoskeletal or cardiovascular impairment.

In the PD group participants had a mean age of 64.6 ± 5years (ranging between 56 and 73 years), and had been diagnosed with PD for 3.1 ± 1.3 years (ranging between 1 and 5 years). Motor impairment was assessed using the Unified Parkinson's Disease Rating Scale where participants' mean score was 29.9 ± 11.5 (ranging between 15 and 46). Eight participants were categorised as being at stage 2 of the disease, and two at stage 3 (Hoehn & Yahr, 1967). No patients reported or exhibited freezing of gait. The control group had a mean age of 63.9 ± 4 years. Ethical approval for the study was granted by The Office of Research Ethics in Northern Ireland and was carried out in accordance with the principles laid down by the declaration of Helsinki.

2.2.2. Recording footstep sounds

The footstep sounds used in the current study were identical to those used in a previous study (Young et al., 2013). To record the sounds we asked a young healthy male (21 years old) to walk along a six meter path, where a 60 cm^2 section had been removed and filled with coarse gravel. The sounds of individual footsteps made on the gravel were recorded over a range of gait parameters using two microphones (rode nt2). The gait parameters used included two variations of SL; specified using horizontal lines on the walkway separated by 70 cm (medium) or 90 cm (long). Footsteps made at each of the specified SLs were recorded over three cadences (500, 600 and 700 ms intervals) defined using an auditory metronome. For each of these gait parameters, twenty individual footstep sound samples were recorded, combined and synchronized according to the relevant cadence interval (see Fig. 1).

2.2.3. Procedure

Participants' gait kinematics were recorded whilst they walked along a 12 m path (gymnasium floor without any significant markings or patterns) wearing wireless headphones. Section 2 comprised four cueing modalities: (i) verbal instruction (Inst-only), (ii) verbal instruction and metronome (Met+Inst), (iii) Stepping sounds only (FS-only), and (iv) footstep sounds with verbal instruction (FS+Inst), the order of which was randomised.

At the start of the first session participants were asked to walk along the path at their own pace without any cues. This was repeated four times, with a 2 min rest between each walk. These trials were used to represent participants' baseline walking parameters. The mean interval between footsteps in control walking trials was rounded to the nearest 100 ms in order to select the most appropriate cadence from the footstep sound recordings for each participant. It was at this interval that all footstep and metronome cues were presented for that participant for all three experimental sessions. This was done to keep the temporal characteristics consistent between cue modalities. In the control group all participants were cued at 600 ms stepping intervals (meaning control stepping frequencies all fell between 550 ms and 649 ms). Within the PD group 7 participants were cued at 600 ms and 3 at 700 ms.

Within Inst-only and Met+Inst trials participants were verbally instructed to walk with a "normal and comfortable", or "long" SL at the start of each trial. During Met+Inst trials participants were also asked to walk in time to the metronome. Within FS-only trials participants were instructed to walk in a manner that they would expect to make the same sound, were they walking on gravel. FS+Inst trials were identical to FS-only, with the exception that at the start of each trial, participants were verbally informed of the SL represented in the upcoming footstep sound and were instructed to adjust their SL accordingly. Participants completed 2 walking trials within each of the SL conditions, the order of which was randomised. After completing all trials for a given cue modality, participants were required to sit and rest for a minimum of 5 min. This was done in an attempt to minimise any carry-over effects from the previous cueing trials.

In order to avoid fatigue effects each participant was permitted to complete trials from a maximum of four cue modalities in a given session. Therefore, data collection for all three experimental sessions required a minimum of three separate visits from each participant. For all experimental sessions, all participants in the PD group started the walking trials one hour following their previous dose of medication, and each participant started each session at the same time on separate days. Also, to ensure participants' perceptions of the footstep sounds were not influenced by any prior instruction during FS-only conditions (and during other experimental conditions described in Sections 3 and 4); FS+Inst trials were carried out at the end of the experimental protocol in the final session.

At the start of each trial containing a sound cue participants were instructed to listen to the sound for as long as they wished and start walking when they were ready. When no acoustic stimuli were presented (i.e., during Inst-only trials), participants were given instruction regarding their intended SL and asked to start walking when they were ready. Prior to gait initiation participants stood at a position indicated by the experimenter and were given the option to hold on to a rail for support.

Participants wore 10 mm spherical reflective markers on the heel of each foot so that the spatial-temporal characteristics of their walking could be recorded at 200 Hz using 18 Qualisys (Oqus3) motion capture cameras (Qualisys Ltd, Sweden). Mean SL was calculated as the absolute displacement between heel markers at the time of consecutive heel contacts. Mean step duration was calculated as the duration between successive heel contacts. Relative change in SL during cueing trials was calculated as a percentage change relative to the SL observed during control walking: $((\text{mean cued SL}/\text{control SL}) \times 100) - 100$. The variability of both SL and step duration was calculated as the standard deviation of values for all steps recorded within each subcondition. The relative percentage change in variability was calculated in the same manner as described above for mean SL.

Both within subject, and between group differences in: (i) percentage change in SL, (ii) mean step duration, (iii) percentage change in variability of SL, and (iv) percentage change in variability of step duration, was assessed using a mixed ANOVA (cue modality $(4) \times$ group $(2) \times$ SL (2)). All post hoc analyses were carried out using Bonferroni-corrected *t*-tests. Four additional one-way ANOVA were carried out to identify any significant group differences in any of the four independent variables listed above during control walking trials.

2.3. Results

2.3.1. Mean step length

Results for participants' percentage change in SL showed a significant three-way interaction between participant group, cue

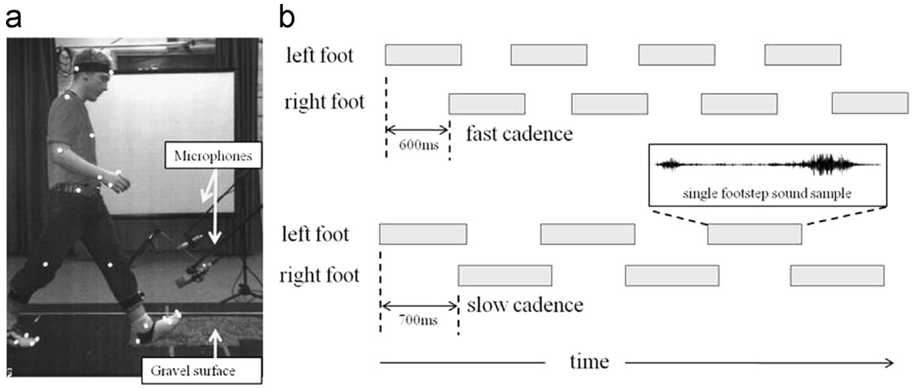

Fig. 1. (a) Cross-sectional view of experimental setup for recording sound stimuli. (b) Method for concatenating sound recordings of individual footsteps into a continuous sequence.

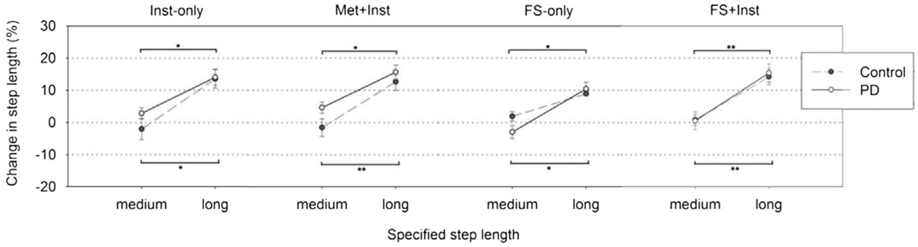

Fig. 2. Percentage change in mean step length relative to that recorded during baseline trials. Error bars represent standard error of the mean. $^{*}p<.01$. $^{**}p<.001$.

modality and specified SL ($F_{(3,54)}=2.892$, $p<.05$, $\eta_p^2=.658$). Although Fig. 2 shows that percentage change in SL was reduced in the control group during Inst-only and Met+Inst, conditions, post hoc analysis showed no significant differences between participant group or cue modality. Presumably this was due, in part, to an increase in between-subject variability during Inst-only and Met+Inst conditions (as indicated by the error bars in Fig. 2). However, in all four cue modalities, participants in both groups significantly adapted their SL according to that depicted in the respective cue (Fig. 2). ANOVA showed a significant difference between groups in mean SL during control walking trials ($F_{(1,19)}=13.294$, $p<0.01$). Mean values were 66.8 ± 5.6 cm and 56.7 ± 7.7 cm for control and PD participants, respectively.

2.3.2. Temporal deviation from guide

Results for temporal deviation showed no main effects or interactions. No significant differences were found between groups for mean step duration during control walks (571 ms ± 33 ms for controls and 612 ms ± 50 ms for PD patients).

2.3.3. Variability of gait

Results for the percentage change in variability of SL showed a significant interaction between participant group and cueing modality ($F_{(3,54)}=13.992$, $p<0.001$, $\eta_p^2=.942$). In the PD group, across both SL conditions, SL variability was significantly lower within the FS-only and FS+Inst cue modalities compared to Inst-only and Met+Inst cues. Furthermore, compared to the control group, PD patients showed significantly reduced variability within FS-only and FS+Inst cues (Fig. 3a). ANOVA showed a significant difference in SL variability between groups during control walking trials ($F_{(1,19)}=17.899$, $p<0.01$). Mean step length s.d.s were 3.2 cm and 5.4 cm for control and PD participants, respectively.

The percentage change in the variability of step duration also showed a significant interaction between participant group and cue modality ($F_{(3,54)}=4.359$, $p<0.01$, $\eta_p^2=.845$). In the PD group, across all SL conditions the variability of step duration was significantly lower within FS-only and FS+Inst cue modalities compared to Inst-only trials. Also, compared to the control group, PD patients showed significantly reduced variability within Met+Inst, FS-only, and FS+Inst cue modalities (Fig. 3b). ANOVA showed a significant difference between groups in the variability of step duration during walking trials ($F_{(1,19)}=4.624$, $p<0.05$). Mean duration s.d.s for these baseline trials were 32 ms and 44 ms for control and PD participants, respectively.

2.4. Discussion

Results from Section 2 show that participants were able to significantly adapt their SL in accordance with the information conveyed in footstep sounds (Fig. 2). These results represent a novel development for, as far as we know, this is the first instance where spatial components of gait have been specified within an acoustic cue and successfully perceived and used by PD patients to adapt their own SL. These results support previous claims that acoustically-derived perceptions of well-learned actions are sensitive to changes in movement amplitude (Young et al., 2013).

Many researchers have suggested that sensory cueing is effective in people with PD because of the neural pathways through which the sensory information is processed; namely pathways that bypass the basal ganglia, such as cortical and pre-motor areas (Rochester et al., 2007; Cunnington, Iansek, Bradshaw, & Phillips, 1995; Debaere, Wenderoth, Sunaert, Van Hecke, & Swinnen, 2003). In the absence of any electrophysiological or haemodynamic data, we are unable to identify specific neural processes responsible for the benefits described when PD patients imitated the footstep sounds. However, the within subject adaptations in SL were very similar between groups (Fig. 2), indicating that the basal ganglia are unlikely to play a major role in real-time action-imitation.

Within both FS-only and FS+Inst cueing modalities PD patients' temporal and spatial variability reduced by a remarkable ~25% and ~35%, respectively (Fig. 3a and b). Although noteworthy, it is not particularly surprising that the reductions in gait variability shown in PD patients were not replicated in the control group, as when largely

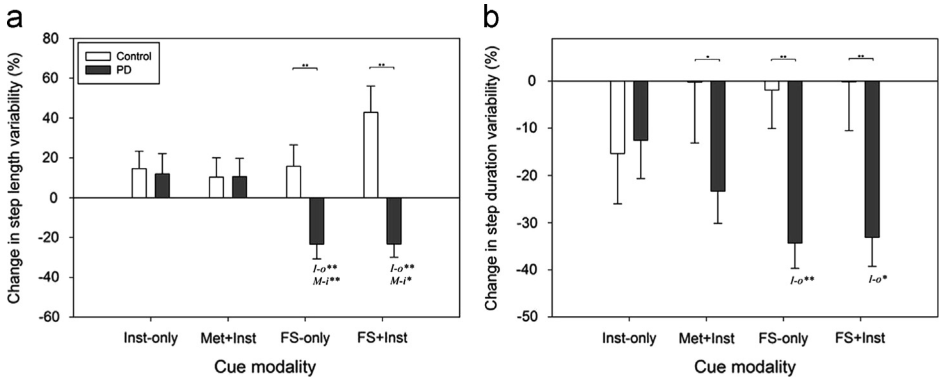

Fig. 3. Figures show percentage change in variability of gait with respect to values recorded during baseline trials. Plots a and b show spatial and temporal variability, respectively. *I-o* and *M-i*, represent significant differences to Inst-only and Met+Inst cue modalities, respectively. Error bars represent standard error of the mean. $^{*}p < .01$. $^{**}p < .001$.

automatic/habitual stepping actions become goal-directed (i.e., when using sensory cues) (Redgrave, Prescott, & Gurney, 1999) one might expect movement consistency to be compromised in individuals where the habitual control of walking is preserved (Wulf & Prinz, 2001). This is demonstrated by the significantly lower gait variability in the control group, compared to the PD group during control walking trials.

It is more relevant to question how gait variability was reduced to such an extent in PD patients when using footstep sounds, compared to the attentional strategies. In the absence of any temporal information, PD participants still reduced the variability of their stepping duration by ~12% during Inst-only trials. However, the extent of these reductions was significantly less compared to those shown during either of the cue modalities using footstep sounds (Fig. 3a). Whilst the magnitude of the reduction in temporal variability was approximately matched in Met+Inst trials compared to FS-only and FS+Inst, spatial variability actually increased during Met+Inst trials by ~10%.

Azulay et al. (1999) showed that the benefits derived from using visual-spatial cues (horizontal lines placed on the floor) were lost when patients walked over the same cues illuminated only by stroboscopic lighting (thus suppressing the dynamic component of vision). This study demonstrates the importance of presenting spatial information in a continuous dynamic fashion and leads us to question whether the same principles can be applied to sensory cueing strategies in the auditory domain. For instance, it is possible that the continuous nature of the gravel sounds may have allowed participants to synchronise their ongoing actions to the continuous perception of the footstep actions. This manner of reciprocal audio-motor activity could provide a means of detecting errors and discrepancies between the observed and executed actions (Iacoboni, 2008), to improve the regularity with which PD patients could execute stepping actions. In contrast, it is possible that the ambiguity of verbal cues in combination with a lack of online sensory information available for participants whilst walking is likely to have contributed to the relatively increased SL variability seen during Inst-only and Met+Inst cue conditions compared to FS-only and FS+Inst.

When using both FS+Inst and Met-Inst cues participants were explicitly told what their SL should be. The conditions differed in that during FS+Inst trials, participants' conscious intention to perform a given SL was accompanied by congruent sensory information. We suggest that the specificity of the gravel sounds in matching the required walking action reduced the extent to which participants had to independently generate motor sequences (processes involving the basal ganglia (Castiello, Ansuini, Bulgheroni, Scaravilli, & Nicoletti, 2009)), as participants could simply constrain their actions to temporal dynamics of the ongoing sound (Debaere et al., 2003). This work marks a novel approach to sensory cueing, by exploiting the neural processes involved in the perception of action through sound. However, these findings lead us to question whether we can identify the fundamental source of dynamic information that is being picked up and used by participants to adapt their SL. That is, it may be possible to isolate the invariant information in the auditory event that conveys the spatial-temporal qualities of a stepping action, and use this to synthesise effective cue sounds.

3. Session 2

3.1. Introduction

SL is predominantly modulated by the forces exerted by the foot onto the walking surface during the stance phase of gait (Varraine et al., 2000). Physical laws assert that changes in this kinetic interaction will alter the characteristics of the sound energy lost through the collisions between gravel particles, thus providing a framework for kinetic-acoustic transformations.

Previous work from our laboratory has shown that young healthy adults' capacity to perceive and re-enact spatial changes to gait from recorded sounds of footsteps is extended to when they listen to synthesized sounds that are derived solely from the basic kinetic properties of the interactions between the feet and walking surface. The purpose of Section 3 in the current study was to assess whether PD patients and age-matched controls were also able to significantly adapt their own SL when walking to the same synthesized sounds as used by Young et al. (2013).

With respect to the synthesis of the footstep sounds, the kinetic-acoustic transformation process had to meet two criteria: (a) that the sound intensity envelope of the resultant sound was directly specified by the kinetic information of the referent event, and (b) that the synthesis process was based on the physical interactions within the referent event (collisions between gravel particles) so that the resulting sound would resemble that of a footstep. Here, the comparison between the synthesized and real recorded footstep sounds might be compared to a common technique used in visual perception studies, where point-light displays are employed as simplified visual representations of a given action (Schouten, Troje, Vroomen, & Verfaillie, 2011).

Results from Section 2 showed that the magnitude of adaptations to SL seen in PD patients was highly comparable to that shown by controls, suggesting that the neural processes used by healthy adults to perceive SL represented by the FS-only sounds are preserved in PD patients. Based on the observation that young healthy adults can perform adaptations in their SL with comparable success when re-enacting both recorded footsteps and their synthesised counterparts (Young et al., 2013), we suggest that, sounds that are synthesised to represent the kinetic dynamics of foot stepping actions on gravel will provide PD patients with sufficient information to enable effective gait cueing. Therefore, we predict that both participant groups will produce similar adaptations to their gait when walking to the synthesized sound cues compared to the real recorded footstep sounds presented in Section 2 (Fig. 2).

3.2. Methods

3.2.1. Sound synthesis

The specific details regarding the production of the synthesized footstep sounds are described in detail in Young et al. (2013). The same actor whose footsteps were recorded and used as sound samples in Section 2 repeated a further 20 walking trials for each set of gait parameters (2 × SL, 3 × cadence). The area formerly filled with gravel was fitted with a forceplate (AMTI, Watertown, MA). Ground reaction force (GRF) vectors between the foot and the plate were recorded for each of the walking trials from which the mean of all 20 trials within each gait parameter was calculated for each of the six gait parameters (see Fig. 4). The mean GRF vectors were then entered in to the acoustic synthesis program described in Young et al. (2013). This synthesis program (adapted from Farnell (2007)) uses the GRF vector to modulate both the intensity envelope and central frequency of a bandpass filter applied to a stochastic noise impulse signal, to generate synthetic gravel step sounds that correspond to the planter force of the actor's forceplate recordings (Rodger, Young, & Craig, 2013).

For each of the six gait parameters, the output of the synthesis program was recorded over 20 trials and synchronized according to the specified cadence in the same manner as described in Section 2 (see Fig. 1). It is noteworthy that, as the process of synthesizing the footstep sounds were based on a series of noise signals, the output for each individual recording contained variations from step to step, as did the real sound recordings.

3.2.2. Procedure

All participants and data analyses used in Section 3 were the same as those described in Section 2. It was important to keep these factors consistent because statistical analysis was carried out to compare results between Sections 2 and 3 (described below). However, the sound samples used in Section 3 were the synthesized sound samples of gravel steps. As described in Section 2, the extents to which PD and control groups could perceive SL within the synthesized footstep sounds (Synth-only) was examined through the inclusion of a condition where the SL represented in each footstep sound was verbally clarified to the participant prior to when the respective cue started to play (Synth+Inst). To ensure that participants' perceptions of the footstep sounds were not influenced by any prior instruction during Synth-only conditions, Synth+Inst trials were carried out along with FS+Inst trials at the end of the experimental protocol for the whole study.

As described in Section 2, within each cue modality there were two SL conditions representing either a medium or long SL. In order to provide a comparison between Synth-only and Synth+Inst cue modalities and their real recorded counterparts (FS-only and FS+Inst) data from all four dependent variables previously described were entered in to a mixed ANOVA (of the same structure to that described in Section 2) (cue modality (4) × group (2) × SL (2)).

In order to provide a comparison between Synth-only and Synth+Inst cue modalities and Inst-only and Met+Inst cues, data from all four dependent variables were entered in to a further mixed ANOVA consistent with that described above. All statistical procedures were consistent with that described in Section 2.

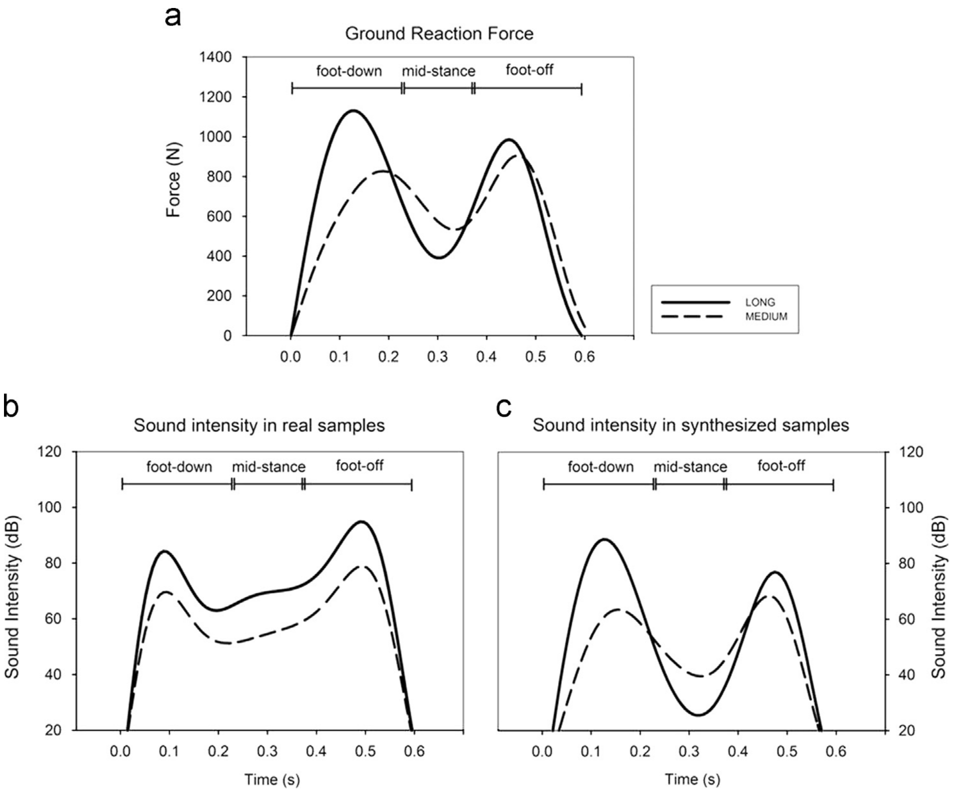

Fig. 4. (A) Sample ground reaction force vectors recorded during the stance phase of gait at medium (70 cm) and long (90 cm) step lengths. Panels B and C show values representing sound intensity levels within real (B) and synthesized (C) samples. Foot-down, mid-foot, and foot-off provide a reference to the three main phases of the stance.

3.3. Results

3.3.1. Mean step length

Results for participants' percentage change in SL (relative to baseline walk) showed a significant three-way interaction between participant group, cue modality and specified SL ($F_{(3,54)}=4.508$, $p<0.01$, $\eta_p^2=.645$). Post hoc analysis showed that the control group significantly adapted their SL in all cue modalities according to that depicted in the sensory cue. This was also the case for PD patients, with the exception of Synth-only trials. Within the control group, post hoc analysis showed significant differences between cue modalities. However, in the PD group SL was significantly shorter in Synth-only trials compared to all other cue modalities containing a long SL cue. With respect to between-group differences, post hoc analysis showed that compared to control participants, PD patients demonstrated significantly less of an increase in SL from baseline within Synth-only trials, but only when cues depicted a long SL (see Fig. 5).

When comparing results from trials containing synthesized sound samples to Inst-only and Met+Inst cues, ANOVA showed two significant two-way interactions between cue modality and cue SL ($F_{(3,54)}=4.956$, $p<0.01$, $\eta_p^2=.905$) and cue modality and participant group ($F_{(3,54)}=5.157$, $p<0.01$, $\eta_p^2=.892$). Post hoc analysis showed that PD patients produced significantly longer SL across both medium and long SL conditions in Inst-only and Met+Inst conditions compared to Synth-only ($t(19)=4.258$, $p<.001$) and ($t(19)=4.940$, $p<.001$), respectively. PD patients also produced longer SL in Met+Inst compared to Synth+Inst trials ($t(19)=3.835$, $p<.001$).

3.3.2. Temporal deviation from guide

Results for temporal deviation showed no main effects or interactions.

3.3.3. Variability of gait

Results for the percentage change in variability of SL showed significant main effects of both group ($F_{(1,18)}=14.186$, $p<0.01$, $\eta_p^2=.868$) (where control participants showed a relative increase in variability compared to PD patients) and cue modality ($F_{(3,54)}=5.918$, $p<0.01$, $\eta_p^2=.741$). Post hoc analysis showed that, across groups and SL conditions, SL variability was lower in Synth-only trials ($-9.3\%\pm30\%$) compared to FS+Inst ($+9.8\%\pm47\%$) ($t(39)$ -3.635, $p<.01$) and Synth+Inst ($+44.7\%\pm121\%$) ($t(39)$ -3.635, $p<.01$) (Fig. 6a).

The percentage change in variability of step duration showed a significant main effect of participant group ($F_{(1,18)}=16.475$, $p<0.01$, $\eta_p^2=.970$), where the PD group showed a substantial percentage reduction in step duration variability compared to the percentage change recorded in the control group. There was no effect of sensory modality or SL condition. Across all SL conditions and cue modalities the percentage change in temporal variability of step duration was $+0.1\%\pm34\%$ and $-31.0\%\pm17.9\%$ in the control and PD groups, respectively (Fig. 6b).

When comparing results for the percentage change in the variability of SL from trials containing synthesized sound samples to Inst-only and Met+Inst cues, ANOVA showed a significant two-way interaction between mode and group ($F_{(3,54)}=5.918$, $p<0.01$, $\eta_p^2=.774$). Post hoc analysis showed that PD patients' SL variability was significantly reduced in the Synth-only cue condition compared to Inst-only and Met+Inst (($t_{(19)}=4.741$, $p<.01$) and ($t_{(19)}$ 3.959, $p<.01$), respectively). Percentage change in SL variability was also significantly reduced in the PD group within the Synth-only trials, compared to controls ($t_{(39)}$ 2.281, $p<.05$).

When comparing trials containing synthesized sound samples to Inst-only and Met+Inst cues, results for the percentage change in variability of step duration showed a significant two-way interaction between mode and group ($F_{(1,18)}=4.359$, $p<0.01$, $\eta_p^2=.782$). Post hoc analysis showed that within the PD group, temporal variability was significantly reduced in Synth-only and Synth+Inst cue conditions compared to Inst-only ($t_{(19)}$ 3.09, $p<.01$) and Met+Inst ($t_{(19)}$ 2.739, $p<.05$), respectively. However, no significant differences were found between Met+Inst trials and either condition containing synthesized sound samples.

3.4. Discussion

3.4.1. Spatial adaptation in imitation depends on ecological validity of cue for PD patients

Results from Section 3 illustrate the inability of PD patients to re-enact changes in SL within the synthesized sound samples. Within the Synth-only condition, not only did PD patients fail to produce significant adaptations to their SL between medium and long SL cue conditions, but the percentage change in SL was significantly lower during long SL conditions, compared to when patients used the real sound recordings as part of the FS-only and FS+Inst conditions (Fig. 5). Of particular interest is the finding that, whilst the control group showed significant adaptations to their SL within both Synth-only and Synth+Inst conditions, the PD group only showed such adaptations within Synth+Inst trials. These results are contrary to what we had predicted, and prompt an intriguing discussion in to how PD serves to compromise the perception of SL when sounds are synthesized from kinetic data rather than recorded.

PD is traditionally considered to be a motor impairment. However, evidence is accumulating to suggest that hypokinesia in PD may be linked to deficits in the ability to process and integrate sensory information into motor plans for action (Bloxham, Dick, & Moore, 1987; Sheridan, Flowers, & Hurrell, 1987; Koop, Hill, & Bronte-Stewart, 2013). For example, during non-visually guided arm movements, PD patients will overestimate their own movement amplitude and increase movement error compared to healthy controls (Visell et al., 2009; Moore, 1987; Klockgether & Dichgans, 1994). Similar deficits are also evident in the perception and production of speech, where PD patients will overestimate the volume of their own speech. The result of this perceptual bias is that PD patients will tend to compensate by reducing the volume of

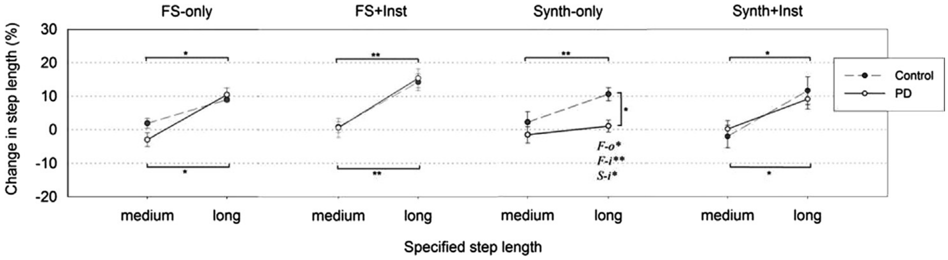

Fig. 5. Percentage change in mean step length relative to that recorded during baseline trials. *F-o*, *F-i*, and *S-i* represent significant differences with respect to FS-only, FS+Inst and Synth+Inst trials, respectively. Error bars represent standard error of the mean. *$p<.01$. **$p<.001$.

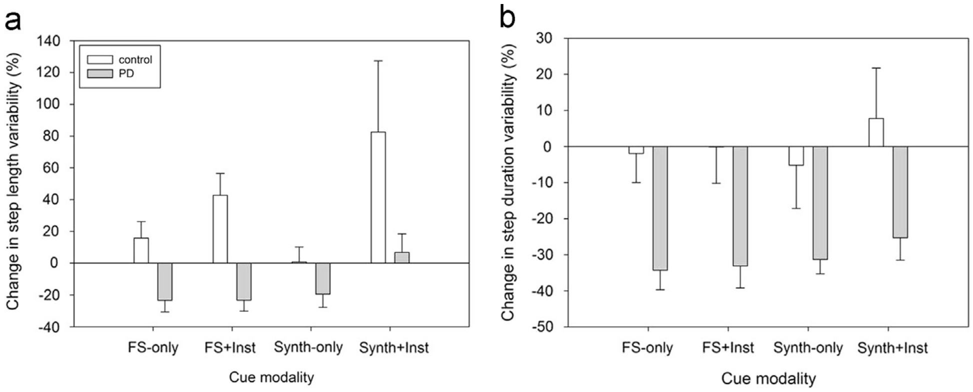

Fig. 6. Figures show percentage change in variability (s.d.) of gait with respect to values recorded during baseline trials. Plots a and b show spatial and temporal variability, respectively. Error bars represent standard error of the mean.

their own speech (hypophonia) (see Kwan & Whitehill, 2011 for review). However, there are examples in the literature that contradict this finding. For example, Dromey and Adams (2000) compared the perception of loudness of warbled tones, participants' own voices (against an intensity anchor), and production of sustained phonation, and found no differences between PD patients and healthy controls. As shown in Fig. 4, one of the major sources of invariant information that specified SL within the synthesized sound samples was sound intensity. Indeed, the magnitude of oscillations in sound intensity was greater in synthesized sounds compared to the real recorded sounds (Fig. 4). Therefore, if the perception of SL afforded by recorded sounds was achieved solely though oscillations in sound intensity, one would expect similar or greater adaptations to SL in both groups during Synth-only trials. Clearly this was not the case in the PD group, yet these same patients were able to successfully adapt SL during FS-only cues. Taken together, these results show that any potential PD-related deficits in the perception of loudness/sound intensity reported in the literature (Kwan & Whitehill, 2011) are unlikely to account for between group differences in SL adaptations during Synth-only trials.

The reason for including both FS+Inst and Synth+Inst trials was to provide a comparison where we could be certain that participants had declarative knowledge of SL within each of the sounds they imitated. The relative inability of PD patients to significantly adapt SL within Synth-only, compared to Synth+Inst trials indicates that they were unable to explicitly perceive SL within the synthesized sounds.

Due to the nature of the synthesis process we can assume that many subtleties of real recorded sounds, such as the immeasurable degree of variation that will exist in the nature of the individual collisions between gravel particles under the foot, will not have been represented within the synthesized sounds. If there are other auditory parameters present in the recordings that co-vary with kinetics of foot-steps on gravel, their absence in the synthesised sounds may have made it harder to pick up information about corresponding spatial-temporal gait parameters. This difference could be responsible for the inability of PD patients to perceive SL within the synthesised sounds.

The finding that the control group produced significant and very similar adaptations in SL between FS-only and Synth-only trials suggest that comparable perceptual processes were used (Young et al., 2013). In the absence of hemodynamic or electrophysiological data, we can only speculate as to what changes in neural activity occurred within the PD group between FS-only and Synth-only cue conditions. However, the results from Section 3 suggest that during Synth-only trials, the particular mapping of kinetic data to sound synthesis was insufficient to bypass affected neural regions affected by PD and invoke an appropriate auditory-driven motor response.

3.4.2. *Gait variability*

Results for the change in variability of SL showed that whilst there was a main effect of cue modality, this was found in conjunction with a significant increase in the variability of SL in control participants compared to the PD group. Therefore, as shown in Fig. 6a, any significant differences between cue modalities are likely to have been driven by the increased variability shown by control participants rather than the PD group. In addition, results for the change in the variability of step duration showed no differences between cue modalities within the PD group. We can therefore presume that the reductions in variability shown during FS-only and FS+Inst trials in Section 2 are also evident in the PD group during Synth-only and Synth+Inst trials. These findings show that ecological validity is not a critical factor in inducing reductions in gait variability in PD, and that a sonification of the basic kinetic form of the action is, in principle, sufficient to induce reductions in both spatial and temporal gait variability. For the current study, it may be the case that the kinetic-synthesis mapping allowed patients to follow the spatial-temporal envelope conveyed by the sounds consistently, even if they were unable to recreate the magnitude of the actions. This finding provides encouragement for the development of future synthesized cueing tools designed to afford the perception of SL, such as re-modelled sound synthesis paradigms and bio-feedback systems.

Aside from the psychological theory that is addressed in the current study, it is important to consider the practical applications for using acoustic stimuli to cue both spatial and temporal components of gait in PD patients. Tamir, Dickstein, and Huberman (2007), suggested that the use of motor imagery serves to bypass the circuitry involving the basal ganglia and supplementary motor area through the recruitment of neurons in pre-motor areas. It is, therefore, of practical and theoretical significance to consider whether the benefits to gait shown in Sections 2 and 3 can be achieved in the absence of online cue information, and instead through mental imagery of the respective sound and action.

4. Session 3

4.1. *Introduction*

The results from the previous two sessions have shown that continuous acoustic guides can be effective in inducing significant adaptations in SL, but also remarkable reductions in both spatial and temporal variability of PD patients' gait. However, such adaptations in mean SL are only realised when the sound stimuli are recorded footstep actions rather than synthesised from footstep kinetics (see Fig. 4). The purpose of Section 4 was to explore avenues to exploit the putative function of sensorimotor neurons by evaluating the potential for PD patients to exercise imagery of the footsteps that they perceived within the sound cues immediately prior to the start of the walking trial.

There are many examples in the literature where evidence has shown that healthy adults can perform motor imagery of themselves walking. For example, when imagining themselves walking uphill, downhill, or at different speeds, the relevant adaptations to gait are reflected in the actual walking of young adults, such that participants would walk slower when imagining walking uphill (Courtine, Papaxanthis, Gentili, & Pozzo, 2004). These suggestions are supported by studies showing bilateral activity in the supplementary motor area and primary sensori-motor cortex when healthy adults perform actual or simulated walking (Malouin, Richards, Jackson, Duman, & Doyon, 2003; Bakker, de Lange, Helmich, Scheeringa, & Bloem, 2008; Iseki, Hanakawa, Shinozaki, Nankaku, & Fukuyama, 2008). Therefore, the neural systems associated with motor imagery may provide a means of retaining a perception of the relevant stepping action that participants can imitate in a similar fashion to that shown in the previous two sessions.

Motor imagery is frequently used as a therapeutic tool with PD patients (for a review see Malouin & Richards, 2010), and has been shown to be beneficial in improving functional performance and reducing bradykinesia (Tamir et al., 2007). As such, whilst there are reports that PD patients experience difficulties in performing motor imagery (Thobois et al., 2000), and executing imagined actions (Yaguez, Canavan, Lange, & Homberg, 1999), there appears to be a consensus in the literature that motor imagery is a beneficial cognitive strategy to employ in physical therapy settings with PD patients (Morris, 2000; Tamir et al., 2007). However, within this body of literature there is an emphasis on training motor imagery in PD patients; a process that is likely to place significant demands on potentially compromised cognitive resources (Baker et al., 2007; Rochester et al., 2004). There is less information on how motor imagery might be enhanced in PD patients by exploiting existing well-learned audio-motor mappings for a specific action, such as walking. In this sense, using an acoustic representation of an action will, as demonstrated in Section 2, afford specific motor representations of an action that the observer could subsequently retain and imitate even when the stimulus is no longer present. The current experimental session sought to examine whether PD patients and healthy controls could maintain a 'motor-image' of specific footstep actions in conditions where they could not concurrently perceive the relevant actions through sound.

If PD patients are able to exercise imagery of the actions that are perceived within the sound cues, we would expect the same benefits shown in Section 2 within the FS-only cue condition to be preserved in trials where PD patients attempted to imagine and re-enact the steps perceived within those same sound samples. Conversely, the finding that PD patients are comparatively unable to perceive SL from Synth-only cues leads us to suggest that for data concerning adaptations in mean SL, findings from imagery conditions will reflect those shown for the respective cues in Section 3 (i.e., PD patients will only produce significant adaptations to mean SL during imagery trials relating to recorded footsteps and not synthesized sounds).

4.2. Methods

All participants and data analyses used in Section 4 were the same as those described in the previous 2 experimental sessions. It was important to keep these factors consistent because statistical analysis was carried out to compare results between sessions. Data for two of the sensory modality conditions used in Section 4 were taken from results of Sections 2 and 3 (FS-only and Synth-only). These data were compared to results from two further cueing modality conditions (FS + Imagery and Synth + Imagery) where participants were played the sounds of either the recorded or synthesized sounds (sounds consistent with those used during FS-only and Synth-only cue modalities) for 10 s whist stood still (and given the option to hold on to a rail). The sound was then stopped and participants were asked to stand for 10 s and imagine the sound they just heard. After this period participants were verbally prompted to start walking when they were ready, to imagine the sound they just heard and to walk in a manner that they would expect to make the same sound, were they walking on gravel (the final instruction being consistent with that given during FS-only and Synth-only trials).

As described in Sections 2 and 3, within each cue modality there were two SL conditions representing either a medium or long SL. In order to provide a comparison between FS + Imagery, Synth + Imagery, FS-only and Synth-only cue modalities, all four dependent variables previously described were entered in to a mixed ANOVA (of the same structure to that described in Section 2) (cue modality (4) × group (2) × SL (2)).

4.3. Results

4.3.1. Mean step length

Results for participants' percentage change in SL showed a significant three-way interaction between participant group, cue modality and specified SL ($F_{(3,54)} = 2.849$, $p < 0.05$, $\eta_p^2 = .651$).

Within the control group, participants significantly adapted their SL in accordance with that depicted in the cue for all sensory modalities. This was also the case in the PD group, with the exception of the Synth-only sensory modality where no significant adaptation to SL was found (consistent with results for concurrent presentation of cues from Section 3) (see Fig. 7). Whilst there were no significant differences between cue modalities in the control group, the PD group significantly lengthened their SL in both

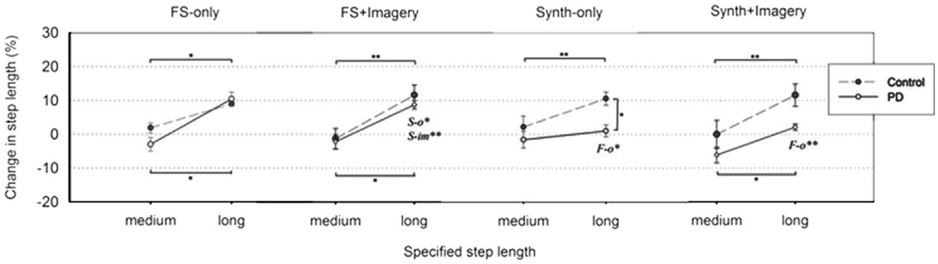

Fig. 7. Percentage change in mean step length relative to that recorded during baseline trials. *F-o*, *S-o*, and *S-im* represent significant differences with respect to FS-only, Synth-only and Synth-Imagery trials, respectively. Error bars represent standard error of the mean. *$p < .01$. **$p < .001$.

FS-only and FS+Imagery trials compared to Synth-only and Synth+Imagery trials, but only during long SL conditions (see Fig. 7). There were no significant differences between trials containing medium SL. Apart from the result previously described in Section 3 (Fig. 2); that the control group produced significantly greater adaptations to their SL during Synth-only trials compared to the PD group, post hoc analysis revealed no significant between-group differences.

4.3.2. *Temporal deviation from guide*

Results for temporal deviation showed no main effects or interactions.

4.3.3. *Variability of gait*

Results for the percentage change in variability of SL showed a significant interaction between participant group and cue modality ($F_{(3,54)}=5.811$, $p<0.01$, $\eta_p^2=.937$). Post hoc analysis showed that across SL cue conditions, compared to control group the percentage change in SL variability was significantly reduced in PD patients in all sensory modalities with the exception of Synth+Imagery trials (see Fig. 8a). Post hoc analysis also showed that within the PD group the percentage change in SL variability was higher during Synth+Imagery compared to all other sensory modalities (see Fig. 8a).

The percentage change in variability of step duration showed a significant main effect of participant group ($F_{(1,18)}=4.908$, $p<0.05$, $\eta_p^2=.554$). There was no effect of sensory modality or SL condition. Across all SL conditions and cue modalities the percentage change in temporal variability of step duration was −12.6% ± 40.2% and −21.2% ± 21.2% in the control and PD groups, respectively (Fig. 8b).

4.4. *Discussion*

The results for Section 4 show that in FS+Imagery trials participants in both groups produced significant adaptations in mean SL between medium and long SL conditions. These results demonstrate that PD patients can maintain imagery an action-sound that can be used to regulate parameters of a concurrent action.

Whilst significant adaptations to mean SL were observed within Synth-Imagery trials in both groups, mean SL within the PD group was clearly below baseline in the medium SL condition (−6.1%) and only slightly above baseline in the long SL condition (2.1%). Within the long SL condition, mean SL was also longer during FS+Imagery compared to Synth+Imagery trials (Fig. 7). Consequently, significant adaptations to SL within Synth+Imagery trials are likely to be driven by the reduction in SL during medium SL trials, rather than a successful increase in SL as observed during FS+Imagery trials. Therefore, during imagery trials, the type of action-relevant acoustic information heard prior to gait initiation becomes an important factor in determining whether PD patients can successfully regulate their movements in accordance with the represented action.

Of particular interest is the finding that reductions in gait variability shown during Synth-only trials were not extended to Synth-Imagery conditions (Fig. 7). Results from Section 3 showed that the type of action-relevant information available within the acoustic cue was not a critical factor in inducing reductions in variability. However, Section 4 has shown that, for synthesized sounds, such reductions are only observed when the acoustic cue is made available to PD patients concurrently during the walking task (Fig. 8). Conversely, when recorded sounds were heard, reductions in gait variability were maintained during imagery. These comparisons support our previous claims that PD patients are capable of utilizing the overall form of the unfolding acoustic information within synthesized sounds to improve the regulation of their actions from step to step (Fig. 6). Yet, during imagery trials when the acoustic information is no longer available, PD patients' variability increases and reverts back towards baseline levels, presumably because sufficient neural resonance (achieved when listening to recorded sounds) was not established at the start of the trial.

It is possible that within FS+Imagery trials participants may have intentionally adapted their SL in accordance with an explicit perception of SL when listening to the sound at the start of each trial. Within this scenario, the neural processes would be similar to that used during Inst-only trials; processes placing additional demands on cognitive processes (Baker et al., 2007; Rochester et al., 2007). If participants were relying predominantly on cognitive strategies to adapt their gait, one would expect similar adaptations to those seen during Inst-only trials in Section 2 (i.e., comparatively less reduction in both spatial and temporal variability compared to FS-only trials). However, we found that the results for percentage change in mean SL and SL variability in FS+Imagery conditions were highly comparable to FS-only conditions and in clear contrast to Synth-Imagery conditions (see Figs. 7 and 8, respectively). Therefore, the behavioural adaptations shown in FS-Imagery conditions are unlikely to have resulted from an attentional strategy to adapt SL following the explicit perception of SL within the sound cue at the start of the trial. Instead, we suggest that the adaptations observed during FS-Imagery trials result from the successful imitation of a motor action that was perceived from sound alone at the start of each trial and maintained

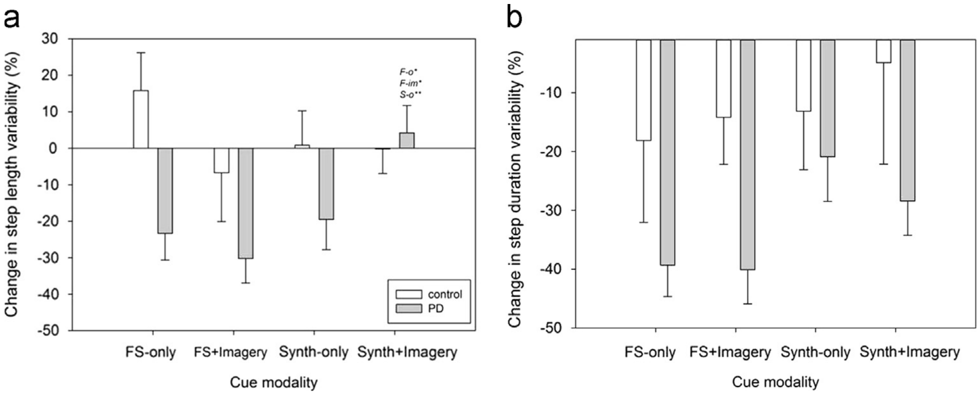

Fig. 8. Figures show percentage change in variability of gait with respect to values recorded during baseline trials. Plots a and b show spatial and temporal variability, respectively. *F-o*, *S-o*, and *S-im* represent significant differences with respect to FS-only, Synth-only and FS-Imagery trials, respectively. Error bars represent standard error of the mean.

during walking as a neural resonance in the absence of external sensory cue information.

5. General discussion

Findings from the current studies show that when listening to the recorded sound of an action, PD does not diminish the ability to perceive and reproduce changes in spatial characteristics of that action (Fig. 2). To our knowledge, this is the first instance where PD patients have been shown to adapt both spatial and temporal characteristics of their gait in accordance with a single acoustic cue. We suggest that the current results represent the beginning of an emerging area of research where both spatial and temporal information for action can be conveyed though sound, and be perceived by listeners by virtue of well-learned associations between common actions (such as walking) and the sound that such actions produce.

There are numerous reports in the literature describing that when people visually observe an action, their subsequent execution of the same action shows visuomotor 'priming' effects (i.e., the movement kinematics of the subsequent action resembled that of the observed action to a greater extent, compared to when no previous action is observed) (Edwards, Humphreys, & Castiello, 2003; Bekkering, Wohlschlager, & Gattis, 2000). Studies using electrophysiological and hemodynamic techniques have repeatedly observed pre-motor activity in healthy adults when a given action is seen (Buccino et al., 2001), heard (Gazzola, Aziz-Zadeh, & Keysers, 2006), and also when executed (Grafton, Arbib, Fadiga, & Rizzolatti, 1996). This work has led to claims that so-called 'sensorimotor' neurons are responsible for processes involving both perception and execution of specific actions (Rizzolatti, & Craighero, 2004). Morris et al. (1996) described how hypokinesia in PD patients reflects a difficulty in activating the motor system. Other research has suggested that sensory cueing is effective in people with PD because of the neural pathways through which the sensory information is processed; namely pathways that bypass the basal ganglia, such as cortical and pre-motor areas (Rochester et al., 2007; Cunnington et al. 1995; Debaere et al., 2003). We suggest that the adaptations to SL shown by both groups during FS-only trials might be considered a form of audiomotor priming. After all, observations of walking actions will illicit activations within the same areas of the pre-motor cortex regardless of whether the stimulus is visual or auditory (Bidet-Caulet, Voisin, Bertrand, & Fonlupt, 2005). Further research should endeavour to provide the direct neurophysiological evidence necessary to better inform this discussion.

Section 3 showed that PD compromises the magnitude of spatial adaptations to gait when the acoustic representation of that action is synthesized and only portrays basic kinetic properties (Fig. 5). As control participants could successfully re-enact changes in SL during both FS-only and Synth-only conditions and PD patients were only successful during FS-only conditions, it is pertinent to consider how PD could compromise the perception of SL within synthesized sounds that are generated from kinetic action information.

We suggest that additional insight can be gained by discussing the current findings with respect to theories relating to the perception and production of speech phonemes. In the study of speech and oral communication, the putative role of sensorimotor neurons has rejuvenated interest in The Motor Theory of Speech Perception first proposed by Liberman, Cooper, Shankweiler, and Studdert-Kennedy (1967). The theory was first designed to account for the problem that speech phonemes do not consistently map on to the properties of the sound that they produce, largely because of acoustic distortion that results from coarticulation (see Galantucci, Fowler, & Turvey, 2006, for a review). The theory posits that when listening to speech sounds we do not perceive speech sounds as sounds per se, but rather the intended oral gesture of the speaker. As such, both a listener and speaker must base their perceptions and phonetic gestures on the same neural template (Liberman et al., 1967; Liberman & Mattlingly, 1985). In other words, the processes involved in understanding the speech of others requires a listener to map the perceived phonetic gestures of others on to representations of those same gestures within their own motor repertoire (Galantucci et al., 2006; Iacoboni, 2008). This perspective suggests that regardless of the acoustic dissimilarities between the real recorded and synthesized sounds, providing the acoustic information was based on the same fundamental kinetic properties of an action; all participants should successfully perceive SL within both sound cues. Although these predictions appear to hold for the control group and for the young adults described by Young et al. (2013), results from Section 3 clearly show that PD compromises such processes. Specifically, the current results show that PD patients require a greater amount of action-relevant acoustic information in order to successfully perceive the basic kinetic form (i.e., spatial attributes) of an action through sound. In other words, with respect to the degree of action-relevant information present within a sound, PD patients have a higher threshold for perceiving movement scale compared to controls.

It is clear that further work is required to identify the specific mechanisms responsible for the PD-related perceptual deficits observed in the current study. This work should focus on distinguishing specific sources of acoustic information available within the recorded sounds that are critical for the perception of SL in PD patients and not controls. Possible candidates include the parameters of the various filters used in the current synthesis process (e.g., to manipulate the attack and decay of each impulse). However, from a practical perspective, in order to provide personalized cues for individual patients, yet circumnavigate the impracticalities of recording footstep sounds, we suggest that granular synthesis may represent a viable solution; a process of triggering individual sound sample blocks ('grains') to represent isolated collisions between gravel particles. As such, experimenters could use individual ground reaction force profiles to regulate the frequency and amplitude at which sound samples are played. This procedure would provide a means of generating individualized acoustic representations of a patient's gait using real recorded sound samples of individual collisions between gravel particles, rather than recordings of an entire stance phase of gait (as described in the current study). The methodology for this type of approach has been eloquently described by O'Modhrain and Essl (2004).

5.1. Reductions in variability are elicited by both recorded and kinetic-synthesised action sounds

One of most compelling findings from the current study is the consistent reduction in both spatial and temporal variability shown when PD patients walked to either real recorded or synthesized cues. Temporal variability was reduced by similar amounts regardless of whether the sound comprised of recorded, synthesized sounds, or a metronome (Figs. 3 and 6b). Therefore, our results suggest that the provision of any temporal cue is sufficient to drive improvements in the form of reduced temporal variability. Instead, it is in the regulation of SL variability that both of the footstep sounds appear to show the greatest benefits, as PD patients reduced their SL variability to a greater extent during FS-only and Synth-only conditions compared to Inst-only and Met+Inst (Fig. 3a and b).

Whereas previous work has shown that continuous acoustic guides for movement are beneficial in reducing the variability of manual pointing movements in young healthy adults (Rodger & Craig, 2011), the current study is, to our knowledge, the first instance where the continuous nature of prospective acoustic information has been shown to be a critical factor in reducing spatial variability of motor performance in PD. As described in Section 2, these results are reminiscent of work on visual cueing conducted by Azulay et al. (1999), who showed that it is the continuous and dynamic information afforded by a cue that is crucial to drive improvements in stepping performance in PD. The current findings indicate that the same conclusions drawn by Azulay et al. (1999) also project to the auditory domain. It may be that, whilst perception of specific action is necessary to induce significant adaptations to SL (as seen in FS-only conditions), availability of continuous dynamic information (in both FS-only and Synth-only cues) provide a continuous temporal reference for movement that facilitates continuous sensory-motor 'coupling', resulting in improved temporal and spatial variability in PD patients. However, when considering the applications of this finding, it is important to consider that not all continuous sounds will convey prospective temporal information. For example, a series of unchanging sine tones may provide a continuous source of acoustic information, yet the dynamics of the sound are unchanging. Therefore, we suggest that PD patients would not derive the same benefits in terms of reduced variability of SL, as there is no continuous temporal reference that permits ongoing movement 'coupling'. Future work should address this question and examine the potential for using dynamic musical tones to specify prospective temporal and spatial information.

One consistent feature of the results from all experimental sessions is the increased variability seen in the control group when walking to the various sensory cues (Figs. 3, 6, and 8). Synchronizing one's walking to an external source of information makes what is normally a largely automatic process, goal-directed. In PD such automatic processes are compromised (Redgrave et al., 2010), which may help to explain why gait variability was significantly higher in the PD group compared to controls during baseline walks (described in Section 2). Whilst this shift in predominant control processes is said to be responsible for the phenomenon of kinesia paradoxica in PD (Rubinstein et al., 2002), it is likely that it will have the opposite effect in people where automatic control processes are preserved. Therefore, the increased variability shown in control participants is likely to reflect repeated online corrections to gait in an attempt to synchronize stepping to the external information, thereby disrupting normal movement sequences and increasing variability.

In Section 4, the findings shown within the FS-Imagery condition are very encouraging as they clearly show that imagery of an action delivers similar benefits to gait as seen during FS-only cues. Previous studies have shown the remarkable capacity of healthy adults to learn and recall complex acoustic information (Levitin, 1994; Levitin & Cook, 1996). Anecdotally, we will all recall having seen someone tapping their hand or foot along with the recollection of a song that they have previously heard and learned. Such behaviour is indicative of a privileged link between auditory and motor areas (Lepage et al., 2010; Zatorre, Chen, & Penhune, 2007). From the results of Section 4, we suggest that such links can be exploited, as imagining the sounds of actions can provide a source of prospective information that PD patients can use to engage the relatively unaffected goal-directed motor control pathways (Redgrave et al., 2010).

5.2. Limitations and future considerations

Whilst the results of Section 2 showed positive results for the use of FS-only and FS+Inst cues, it is important to consider that the real recorded sounds were created by recording the footsteps of a young healthy adult. This was necessary due to many reasons, most notably the number of walks that were required (a total of over 300 walks of the path to record a sufficient number of individual steps). However, there would have been inevitable differences in the acoustic profiles of the sound cue used compared to that which each participant would have made had they been walking on gravel. We suggest that this is not a significant problem concerning the current study as; regardless of how the sounds were recorded the same acoustic stimuli would need to be used for all participants, thereby introducing the same issue. Furthermore, sounds recorded from the young healthy adult as the walking profiles would be free from characteristics of gait relating to PD or increased age. However, we question whether the benefits to gait shown in PD patients would be more pronounced if sensory cues were tailored to the specific gait characteristics of the user, where the action represented by the sound is indicative of an idealised movement profile for a given individual. For example, a sound could be generated that represents a percentage increase in SL from a PD patients' baseline walk. We raise the above issue as a consideration when interpreting the results from the current study, but most importantly because it has consequences for the further development of synthesized action-sounds for use as sensory cues with PD patients. The development of these techniques would pave the way for exploiting the increasing availability of low-cost motion tracking sensors to provide bespoke action-sound cues based on an individual's movement characteristics.

Conflict of interest statement

None of the authors are aware of any financial, personal, or other conflict of interests regarding the work described in this manuscript.

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